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Feedlot efficiency implications on greenhouse gas emissions and sustainability¹

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ABSTRACT: The term sustainable has many meanings, but in agriculture it generally refers to some balance between environmental, social, and economic goals. The objective of this project was to quantify inputs and outputs to assess the sustainability implications of 2 feedlot cattle management systems: Never Ever 3 (NE3) and a conventional (CON) system using metabolic modifiers. Angus-cross steers ($n = 104$) were stratified by BW ($337 \text{ kg} \pm 17$) and randomly assigned to 4 pens per treatment group. The NE3 cattle received no feed additives or implants, whereas CON were implanted with 100 mg of trenbolone acetate and 14 mg of estradiol benzoate on d 1 and 70, and were additionally fed monensin [330 mg/(animal-d)] and tylosin phosphate [90 mg/(animal-d)] in their ration throughout the course of the study, and ractopamine hydrochloride at 254 mg/(animal-d) for the last 29 d on feed. Cattle were shipped on a constant average pen weight basis ($596 \text{ kg} \pm 32 \text{ BW}$). The CON cattle had greater ADG ($1.81 \text{ vs. } 1.35 \text{ kg}$, $P < 0.01$) and were on feed fewer days ($146 \text{ vs. } 188 \text{ d}$, $P < 0.01$) than the NE3 cattle. No significant differences were observed in HCW ($P = 0.072$) or dressing percentage ($P = 0.62$) between treatments ($P > 0.05$); however, CON carcasses averaged larger ribeye area ($87 \text{ vs. } 80 \text{ cm}^2$, $P < 0.01$), greater Warner-

Bratzler shear force measurement (WBSF; $3.46 \text{ vs. } 3.19 \text{ kg}$, $P < 0.01$), and smaller USDA marbling score ($5.4 \text{ vs. } 6.2$, $P < 0.01$), and less backfat thickness ($1.64 \text{ vs. } 1.84 \text{ cm}$, $P < 0.05$) and yield grade ($3.38 \text{ vs. } 3.95$, $P < 0.01$) than NE3 carcasses. Overall, CON cattle consumed 393 kg less DM in the feedlot ($1,250 \text{ vs. } 1,643 \text{ kg}$; $P < 0.05$). No treatment effects were observed for daily methane (CH_4 ; $P = 0.62$) or nitrous oxide (N_2O ; $P = 0.7$) emissions per steer. Assuming a constant emission rate on a DMI basis throughout the course of the feedlot trial, CON feedlot management resulted in a 31% decrease in emissions per finished steer compared with NE3 management. Expressing CH_4 emissions on a carbon dioxide equivalent ($\text{CO}_2\text{-eq}$) basis revealed a 1.10-kg $\text{CO}_2\text{-eq}$ difference per kilogram BW gain ($5.02 \text{ kg of NE3 vs. } 3.92 \text{ kg of CON}$) between the 2 feedlot management systems. Although the metabolic modifiers resulted in additional costs for the CON treatment group, the cost per kilogram of feedlot BW gain was significantly less ($\$1.12/\text{kg vs. } \$1.35/\text{kg}$; $P < 0.05$) than NE3. Both production systems satisfied some sustainability criteria, although neither concurrently fulfilled all of the environmental, social, and economic goals of agricultural sustainability.

Key words: conventional, efficiency, feedlot management, methane, Never Ever 3, sustainability

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INTRODUCTION

The National Environmental Policy Act of 1969 (NEPA, 1970) formally established as a national goal the creation and maintenance of “conditions under which man and nature can exist in productive harmony, and fulfill the social, economic, and other requirements of present and future generations of Americans.” The core of the sustainability ideology revolves around balancing environmental, social, and economic goals. However, trade-offs often exist among these competing goals. Therefore, identification of a single system that satisfies all aspects of sustainability concurrently is difficult. Opinions diverge as to how to define and re-

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search agricultural sustainability (Thompson and Nar-done, 1999). The USDA defines agricultural sustain-ability as “the efficient production of food that meets the current generations’ needs for food and quality of life, enhances the environment and natural resources, and does not compromise the productive capability of future generations” (USDA, 2007). Another definition suggests food systems and practices that “maintain bal-ance by being ethically grounded, scientifically verified and economically viable” (Arnot, 2008). Although sev-eral studies have examined the environmental (Ceder-berg and Mattsson, 2000; Haas et al., 2001; Casey and Holden, 2006; Capper et al., 2008, 2009) and economic (Fernandez and Woodward, 1999) implications of alter-native livestock production systems, few have concu-rrently examined their impact on the 3 goals of sustain-ability (Stern et al., 2005).

Despite the lack of a precise definition, sustainabil-ity has become a selling point, and the marketplace has responded by developing a range of value-added products. One area that has received considerable at-tention is feedlot management, and a market for “sustainable” beef products now exists. Although no formal standards exist for “sustainable” beef, the USDA Ag-ricultural Marketing Service (**AMS**) has developed a process verified program for a “Never Ever 3” (**NE3**) marketing claim. This program is defined as meat from cattle that from birth to death have never received an-tibiotics, growth promotants, or animal by-products (AMS, 2009). Animals that are treated with conven-tional antibiotics due to illness cannot be sold as NE3. This management regimen is quite distinct from con-ventional feedlot management practices that are em-ployed by the majority of the US feedlots where cattle typically receive metabolic modifiers including some combination of anabolic steroids, ionophores and anti-microbial drugs, and β -adrenergic agonists (**BAA**) in the final finishing phase. The objectives of this study were to quantify and compare the sustainability impli-cations associated with the production of a unit amount of feedlot BW gain when comparing conventional and NE3 feedlot management systems.

MATERIALS AND METHODS

This experiment was conducted at the University of California, Davis feedlot facility. Animal care and handling protocols were approved by the University of California, Davis Institutional Animal Care and Use Committee.

Animals and Feedlot Management

Angus-crossbred steers ($n = 104$) sourced from the same calf crop and commercial ranch were randomly allocated into 1 of 2 treatment groups. The NE3 treat-ment was fashioned on the NE3 process verified pro-

gram product definition of the AMS, which excludes the use of antibiotics, growth promotants, or the feeding of animal by-products (AMS, 2009), with the exception of ionophores for the control of coccidiosis. The NE3 cattle in this study received neither hormonal implants nor feed additives. Cattle in the conventional (**CON**) treatment group were implanted with a growth pro-motant (Synovex Choice, Fort Dodge Animal Health, Overland Park, KS; 100 mg of trenbolone acetate and 14 mg of estradiol benzoate) at d 1 and 70. The CON cattle were fed monensin (Rumensin, Elanco, Green-field, IN) at 330 mg/(animal-d) and tylosin phosphate (Tylan, Elanco) at 90 mg/(animal-d) in their ration throughout the course of the study, and for the last 29 d on feed (**DOF**) they were fed the BAA ractopamine hydrochloride (**RAC**; Optaflexx, Elanco) at 254 mg/(animal-d).

The experimental design of the study was a random-ized block design with the period as the block. Thir-teen animals stratified by BW were randomly assigned to a treatment pen with a total of 4 pens per treat-ment group (52 animals per treatment, 4 replications per treatment, $n = 4$). Animals were received from the source ranch at $\sim 254 \pm 27$ kg and were on a starter ration for 49 to 78 d (average of 62 ± 12 d). The trial began when the average BW of cattle in each pen was ~ 337 kg; therefore, the starting date for the pair of pens in each of the 4 periods varied. All pens were given ad libitum access to a corn-based finisher ration (89% DM, 12.8% CP; Table 1). For the last 7 d on feed, cattle in CON pens and their respective contemporaries in NE3 pens were each moved to a cattle pen enclosure (**CPE**) facility for the measurement of greenhouse gas (**GHG**) emissions as described below. Cattle were shipped on a constant end BW basis when the average pen weight reached a target of 590 kg of BW. All animals were also genotyped in the fall of 2008 using the IGENITY Multibreed Panel (IGENITY, Duluth, GA).

Data Collection

The amount of feed given was recorded per pen, and refusals were weighed daily. Feed samples were taken on a monthly basis for proximate analysis. The cattle were fed 30% of daily intake at 0700 h and 70% at 1400 h; slick bunk management (amount of feed given was increased for the next day when all the feed was consumed or conversely was decreased when there was refusal) was followed. Cattle BW were recorded every 28 d before morning feeding and on the day they were shipped from the feedlot. All health treatments were re-corded on each animal. At the processing plant, HCW, ribeye area (**REA**), marbling score, backfat at the 13th rib, and KPH data were collected by USDA personnel, in addition to liver weights and information on whether the liver was condemned. The USDA yield grade was calculated according to USDA guidelines.

Table 1. Diet composition and proximate analysis results (SEM), n = 8

Item	Amount
Ingredient ¹	
Alfalfa hay, %	9.00
Flaked corn, %	77.50
Distillers dried grains, %	4.00
Fat [vegetable (soybean, corn, palm, canola) oil], %	2.00
Premix, % (mineral mix, carrier, ² Tylan, ³ Rumensin ³)	7.50
Total	100.00
Chemical composition	
CP, %	12.80 (0.49)
NDF, %	16.10 (0.38)
Fat, %	5.56 (0.44)
Ash, %	4.26 (0.18)
NFC, %	62.66 (0.63)
GE diet, Mcal/kg of DM	4.45 (0.02)
DE, Mcal/kg of DM	3.82 (0.01)
NE _m , Mcal/kg of DM	2.25 (0.01)
NE _g , Mcal/kg of DM	1.41 (0.003)

¹Percentages on a DM basis.

²Soybean meal.

³Only present in the diet of the conventional treatment group: Rumensin (Elanco, Greenfield, IN) was fed at a rate of 330 mg/(animal·d) and Tylan (Elanco) at 90 mg/(animal·d).

Warner-Bratzler Shear Force Analysis

After 14 d of postmortem aging at 0°C, 1 steak from the LM after the 12th rib was collected per carcass. The steaks were then vacuum packaged and frozen (<−23°C) until analysis was performed. Steaks were shipped on dry ice to the testing facility; the steaks were tested for Warner-Bratzler shear force (**WBSF**) by the Kansas State University Meat Sensory and Cookery laboratory (Manhattan, KS). Steaks were thawed at an average temperature of 0.95°C for 20 h, then moved to a room with an average temperature of 17°C for 1 h, then held at an average temperature of 6.4°C until deboning and trimming. Steaks were deboned and trimmed of excess fat and external muscle in a room with an average temperature of 17°C. Thermocouple wires (30 gauge copper and constantan, Omega Engineering, Stamford, CT) were inserted in the steaks, and internal temperature was monitored using a Doric Minitrend 205 (VAS Engineering, San Francisco, CA). The steaks were cooked in a Blodgett oven (model number DFG-102, The G.S. Blodgett Company Inc. Burlington, VT) set at 163°C. Steaks were turned at approximately 40°C and removed from the oven at 70°C. Internal temperature was recorded when the steaks were placed in the oven and when steaks were removed from the oven. Steaks were then placed on trays, covered with plastic wrap, and refrigerated at approximately an average temperature of 3.2°C until the next day. Six to eight 1.25-cm-diameter cores were taken from each steak parallel to the fiber orientation and sheared perpendicular to the fiber orientation on an Instron Model 5569 Universal Test-

ing Machine (Canton, MA), with the Warner-Bratzler shear head attached. A 50-kg compression load cell was used with a crosshead speed of 250 mm/min.

Cattle Pen Enclosures and Measurement of Gas Emissions

All the animals from each CON pen and their period NE3 pens were moved into a separate CPE for their last 7 d on feed. Each CPE consisted of a dome-like structure measuring 22 × 11 m with dirt floors, pipe fencing, feed bunks, and a water trough. Inlet air (through a cooling pad) and outflow air (through fans with ventilation openings) samples were taken to measure methane (CH₄) and nitrous oxide (N₂O) concentrations. Air ventilation flow rate was also measured to calculate emissions. Data were collected every minute and averaged in 1-h intervals. Emissions were calculated by the following equation:

$$\text{emission rate} = \frac{\text{flow} \times \text{mix} \times 10^{-6}}{\text{MV}} \times \text{MW} \times \text{No. of animals}$$

where flow was the ventilation flow rate in liters per hour, mix was the net gas concentration (difference between inlet and outflow in μL/L), MV was the volume of 1 molar ideal gas in liters per mole (which equals 24.04 at 20°C), MW was molecular weight in grams per mole, and No. of animals was the number of animals in each CPE (in this case, n = 13). Airflow was determined by the rotations per min of the fans and the static differential pressure between inside and outside the CPE recorded using data loggers on 10-min intervals. Temperature and relative humidity inside CPE were recorded on a HOBO RH/T data logger (Onset Comp., Bourne, MA) to correct the airflow rate. Concentrations of target gases in the CPE were continuously measured for CH₄ using a TEI Model 55C Direct Methane, Non-Methane Hydrocarbon Analyzer (Thermo Environmental Instruments, Waltham, MA) and for N₂O using an INNOVA Model 1412 Photoacoustic Field Gas-Monitor (INNOVA, AirTech Instruments, Ballerup, Denmark). All sensors were checked or calibrated as needed before the experiments. The INNOVA 1412 was calibrated by the manufacturer. The TEI55C was calibrated daily at midnight. The overall system, including CPE, sensors, sampling devices, and analyzers was evaluated by introducing 3 L/min pure CH₄ gas into the CPE, mixing it with the ventilation air, and measuring the CH₄ concentration in the outflow of the CPE. Recovery of the introduced CH₄ was 100 ± 10% with the system. Emissions of CH₄ and N₂O output (g/d) proportional to DMI (kg/d) and ADG (kg/d) were calculated by dividing daily output by the number of animals in the CPE, and the average DMI and ADG (during the period in the CPE).

Model for CH₄ Emissions

The observed emissions for CH₄ were converted to a CO₂-equivalent (CO₂-eq) basis using a global warming potential of CH₄ of 23 (IPCC, 2006). The measured CH₄ emissions were compared with those predicted from DMI measurements of each pen during their time in the CPE using the mechanistic models COWPOLL based on Dijkstra et al. (1992) as reported by Kebreab et al. (2008), and MOLLY based on Baldwin (1995).

Statistical Analysis

Feedlot and carcass data from individual animals were analyzed as a randomized pair design using the PROC MIXED procedure (SAS Inst. Inc., Cary, NC) with treatment and period as fixed effects and sire as a random effect. For the following traits, IGENITY score was also included as a regression variable: ADG, marbling, fat thickness, yield grade, REA, and tenderness. Traits collected only on a per pen basis (e.g., amount of feed given) were analyzed using PROC GLM of SAS with treatment and period as fixed effects. The CH₄ and NO₂ data from the CPE were analyzed by calculating the area under the curve and using the generalized least squares fit by REML in R (The R Foundation for Statistical Computing, Vienna, Austria). The model for CH₄ and NO₂ analyses included treatment, day, period, and treatment × day interactions. The chemical composition of the treatment diets analysis was performed using the PROC GLM procedure, with treatment as the fixed effect. The WBSF measurements were evaluated using PROC MIXED with treatment and period as fixed effects, sire and core sample as random variables, and IGENITY tender score and marbling score as fixed regression variables. The liver condemnation data were analyzed as the percentage of livers not condemned per pen using a 2-way proportions test using R, which tested the proportion different in each treatment group.

RESULTS

Feedlot and Carcass Performance

Feedlot performance and carcass characteristics are reported in Tables 2 and 3. The CON cattle had greater ADG ($P < 0.0001$) and G:F ratio (0.241 vs. 0.175, $P < 0.01$). Because the CON cattle grew 34% faster, they were on feed an average of 42 d less than NE3 cattle. The DMI was less for the CON cattle over the course of the study ($P = 0.041$); however, this difference was not significant on a daily basis ($P = 0.22$). The combined cost of the metabolic modifiers and feed consumed in the CON treatment group reduced costs per kilogram of BW gain in the feedlot compared with the NE3 group (\$1.12 vs. \$1.35, $P = 0.011$).

Carcasses derived from CON cattle had significantly larger REA ($P < 0.0001$), less backfat ($P = 0.006$), less

KPH ($P = 0.005$), decreased marbling ($P < 0.0001$), and reduced yield grade ($P < 0.0001$) compared with carcasses derived from NE3 steers. The NE3 group produced carcasses that were more tender ($P < 0.0001$). Forty-two percent of the NE3 carcasses were yield grade 4 and 5, which would likely receive a price discount. Livers from CON cattle were heavier than livers from NE3 cattle ($P = 0.004$). Although there was no significant treatment effect ($P > 0.05$; liver acceptance rate, $P = 0.814$) on overall liver condemnation rate (13% NE3 vs. 10% CON condemned), all of the CON liver condemnations occurred during the slaughter of the cattle in the fourth CON pen. This might be attributable to the observation that the grader during slaughter of the fourth period CON pen appeared to be more stringent on liver condemnation than was the grader that was present on other slaughter days.

During the course of the study there was a therapeutic need to treat some cattle in both treatment groups for a respiratory infection caused by *Histophilus somni* using tulathromycin (DRAXXIN, Pfizer Animal Health, New York, NY) or ceftiofur crystalline free acid (EX-CEDE Sterile Suspension, Pharmacia & Upjohn Company, Division of Pfizer, New York, NY). In commercial settings, such treatments would disqualify NE3 cattle from the value-added natural market. Two of the CON cattle were euthanized as a result of this infection, and in each case an equivalent BW steer was brought into the pen to maintain an equal number of animals in each pen and CPE. The cost of these therapeutic treatments was not accounted for in the current study because it was not uniquely associated with a single treatment group, although the lost opportunity cost of not being able to sell to the value-added natural market would be uniquely associated with the NE3 treatment group.

Table 4 shows the results of the IGENITY Profile score analysis. Marbling score was not found to be significantly associated with WBSF values ($P > 0.1$) and was removed from the WBSF model. Tenderness and marbling were the only traits in which there was a significant association ($P < 0.05$) between the profile score and the target trait phenotype, although it should be noted that the sample size of this data set was less than 100 animals because genotypes were not available on all animals.

GHG Emissions

Average hourly CH₄ and N₂O emissions data are shown in Figure 1. Because of equipment malfunction, GHG measurements were only collected for 2 of the 4 periods, meaning there were only 2 replicates for the measurement of GHG emissions. There was an effect ($P < 0.05$) of time of day and day on CH₄ and N₂O production. There was no treatment effect on daily CH₄ (281.8 g of CH₄ for NE3 vs. 294.6 g of CH₄ for CON/d, $P = 0.62$) or N₂O (4.8 g of N₂O for NE3 vs. 5.7 g of N₂O for CON/d, $P = 0.70$) emissions/steer. Assuming an approximately constant emission rate (DMI basis)

Table 2. Average (SEM) feedlot performance and carcass characteristics of steers finished under Never Ever 3¹ (NE3) and conventional² (CON) feedlot management systems

Item	NE3	CON	P-value
Pens, n	4	4	—
Initial BW, kg	337 (7.91)	337 (7.53)	0.77
Final BW, kg	591 (5.82)	600 (5.74)	0.09
ADG, kg/d	1.35 (0.03)	1.81 (0.05)	<0.0001
Days on feed	188 (7.38)	146 (8.51)	0.01
Feedlot data			
Total kg of feed fed/steer	1,643 (96)	1,250 (119)	0.041
kg of feed (DM)/steer	1,462 (86)	1,112 (106)	0.041
kg of feed (DM)/(steer-d)	7.8 (0.30)	7.6 (0.30)	0.22
G:F	0.18 (0.01)	0.24 (0.016)	0.0019
Feed cost, \$/kg feed (as fed)	\$0.21	\$0.23	—
Implant cost	—	\$4.50/steer	—
Optaflexx cost	—	\$8.70/steer	—
Cost of feed + technology/kg of BW gain	\$1.35 (0.05)	\$1.12 (0.07)	0.011
Carcass data			
Carcasses, n	52	50	—
HCW, kg	362 (3.06)	368 (3.47)	0.072
Ribeye area, cm ²	79.9 (0.09)	87.1 (0.20)	<0.0001
Yield grade	3.95 (0.09)	3.38 (0.12)	<0.0001 ³
KPH, %	2.83 (0.21)	2.51 (0.13)	0.005
Fat thickness, cm	1.84 (0.02)	1.64 (0.02)	0.0061
USDA Marbling score ⁴	6.2 (0.21)	5.4 (0.05)	<0.0001
Dressing %	61.3 (0.30)	61.3 (0.30)	0.62
Liver wt, kg	13.2 (0.38)	14.1 (0.49)	0.02
Liver acceptance rate, %	87 (5)	90 (9)	0.814
Shear force, kg	3.19 (0.77)	3.46 (0.75)	0.004

¹Never Ever 3: no feed additives or implants.

²Conventional treatment: double implantation with Synovex Choice (Fort Dodge Animal Health, Overland Park, KS), fed the ionophores Rumensin and tylosin (Elanco, Greenfield, IN), and for the last 29 d on Optaflexx (Elanco).

³Period effect, $P = 0.04$.

⁴5.00 = Small⁰⁰, 6.00 = Modest⁰⁰, 7.00 = Moderate⁰⁰, 8.00 = Slightly abundant⁰⁰, 9.00 = Moderately abundant⁰⁰.

throughout the course of the feedlot trial, then overall CH₄ and N₂O produced by the CON cattle would be expected to be approximately 31% less for CON steers than for NE3 steers due to the decreased DOF and DMI required to reach the target end BW in the CON group. Expressing CH₄ emissions on a CO₂ equivalent basis resulted in a difference of 1.10 kg of CO₂-eq. (5.02

NE3 vs. 3.92 CON) per kilogram of feedlot BW gain (Table 5a). Both COWPOLL and MOLLY predicted less CH₄ emissions than were recorded (Table 5b); however, predictions from these mechanistic models and experimental observations should not be compared directly unless all of the conditions of the experiment are represented in the models.

Table 3. The USDA quality and yield grade (YG) distributions of carcasses and carcass characteristics of steers finished under Never Ever 3¹ (NE3) and conventional² (CON) feedlot management systems

Treatment	YG <3, %	YG 3 < 4, %	YG 4 and greater, %
Distribution of YG between treatments			
NE3	4 (n = 2)	54 (n = 28)	42 (n = 22)
CON	24 (n = 12)	60 (n = 30)	16 (n = 8)
Distribution of quality grades between treatments			
	Prime, %	Choice, %	Select, %
NE3	11 (n = 6)	85 (n = 44)	4 (n = 2)
CON	0 (n = 0)	84 (n = 42)	16 (n = 8)

¹Never Ever 3: no feed additives or implants.

²Conventional treatment: double implantation, ionophores, and ractopamine-HCl.

Table 4. Significance of sire and the IGENITY multibreed marker score for carcass traits and ADG

Trait	IGENITY score	n	Sire <i>P</i> -value	Regression coefficient ¹	IGENITY score <i>P</i> -value
ADG	ADG	94 ²	0.06	0.006	0.79
Marbling	Marb	93	0.49	0.201	0.04
Backfat	Fat	94	0.18	0.499	0.33
YG ³	YG	95	0.17	-0.058	0.42
REA ⁴	REA	94	0.21	-0.069	0.57
WBSF ⁵	Tenderness	88	0.12	-0.053	0.03

¹Regression coefficient of the scores reported for trait marker panel and observed phenotypes in the test population on the scores reported for the DNA test.

²Sample size variation is due to missing observations (incomplete genotyping).

³Yield grade.

⁴Ribeye area.

⁵Warner-Bratzler shear force is a means of evaluating tenderness.

DISCUSSION

Agricultural production systems frequently present trade-offs among environmental, social, and economic goals, and no single production system is likely to satisfy all aspects of sustainability simultaneously (Stern et al., 2005). Few studies have attempted to quantify how well different feedlot production systems achieve sustainability goals (Wileman et al., 2009). This study aimed to quantify the sustainability implications specifically associated with the production of a kilograms of feedlot BW gain when comparing CON and NE3 feedlot management regimens. Although it is understood that there are sustainability implications associated with the production of the feeder steers that were used in this trial before their arrival at the feedlot (i.e., at the cow-calf operation) which would need to be included in a complete life cycle analysis, the role of feedlot management practices was the sole focus of this study. It is also important to recognize that in commercial feedlot situations it is likely that NE3 cattle would have been finished at a lighter BW than CON cattle due to the increased fat composition of heavier carcasses produced without the use of metabolic modifiers.

There has been a shift away from including untreated control animals in experiments designed to examine the effect of metabolic modifiers on feedlot performance and carcass characteristics (Wileman et al., 2009); however, data such as those presented in the current study are important to determine all of the sustainability implications of producing a unit of BW gain using alternative feedlot management systems. Notably, we selected a constant average pen BW basis as the endpoint for this trial. Others have used this approach (Woodward and Fernandez, 1999), but in commercial settings other endpoints (e.g., constant DOF, quality grade, backfat thickness, or body composition) may be more appropriate. For example, slaughtering at a constant 8-mm backfat endpoint resulted in implanted cattle having both decreased DOF and increased HCW relative to control steers (Berthiaume et al., 2006). Altering the

target endpoint would necessarily alter many of the values reported in this study in a situation-dependent manner.

Economic Implications

The use of implants and feed additives resulted in a 34% increase in feedlot ADG and decreased the resources required to produce a fixed amount of output. As expected the CON cattle grew more quickly and achieved the target market BW an average of 42 fewer days than was required for the NE3 cattle. This resulted in a 21% less feed and technology cost of production (\$1.12 vs. \$1.35) per kilogram of feedlot BW gain. A comparison of the feedlot performance of organic vs. conventional steers by Fernandez and Woodward (1999) showed an even larger effect, with the conventional finishing treatment having better ADG, feed efficiency, heavier end BW, less DOF, and decreased feed costs, which reduced the cost of BW gain by 39% (\$1.36/kg of BW gain for conventional vs. \$1.89/kg of BW gain for organic finishing system). A second paper reporting on this comparison between organic and conventional feedlot steers evaluated the carcass performance of the organic and conventional feeding systems and found the conventionally finished cattle had heavier carcasses, larger REA, and less backfat and intramuscular fat (Woodward and Fernandez, 1999).

Several costs were not accounted for in the present study. Implanting the CON cattle at 70 d would require additional labor to work the cattle through the chute a second time, and some loss in performance would be associated with the procedure. Because of therapeutic need and an animal care protocol mandate, some cattle in each group were treated for bovine respiratory disease. In commercial settings, such treatments would disqualify NE3 cattle from that value-added market. Natural markets are associated with more risk than other branded beef programs, because of the greater opportunity cost associated with having to therapeutic

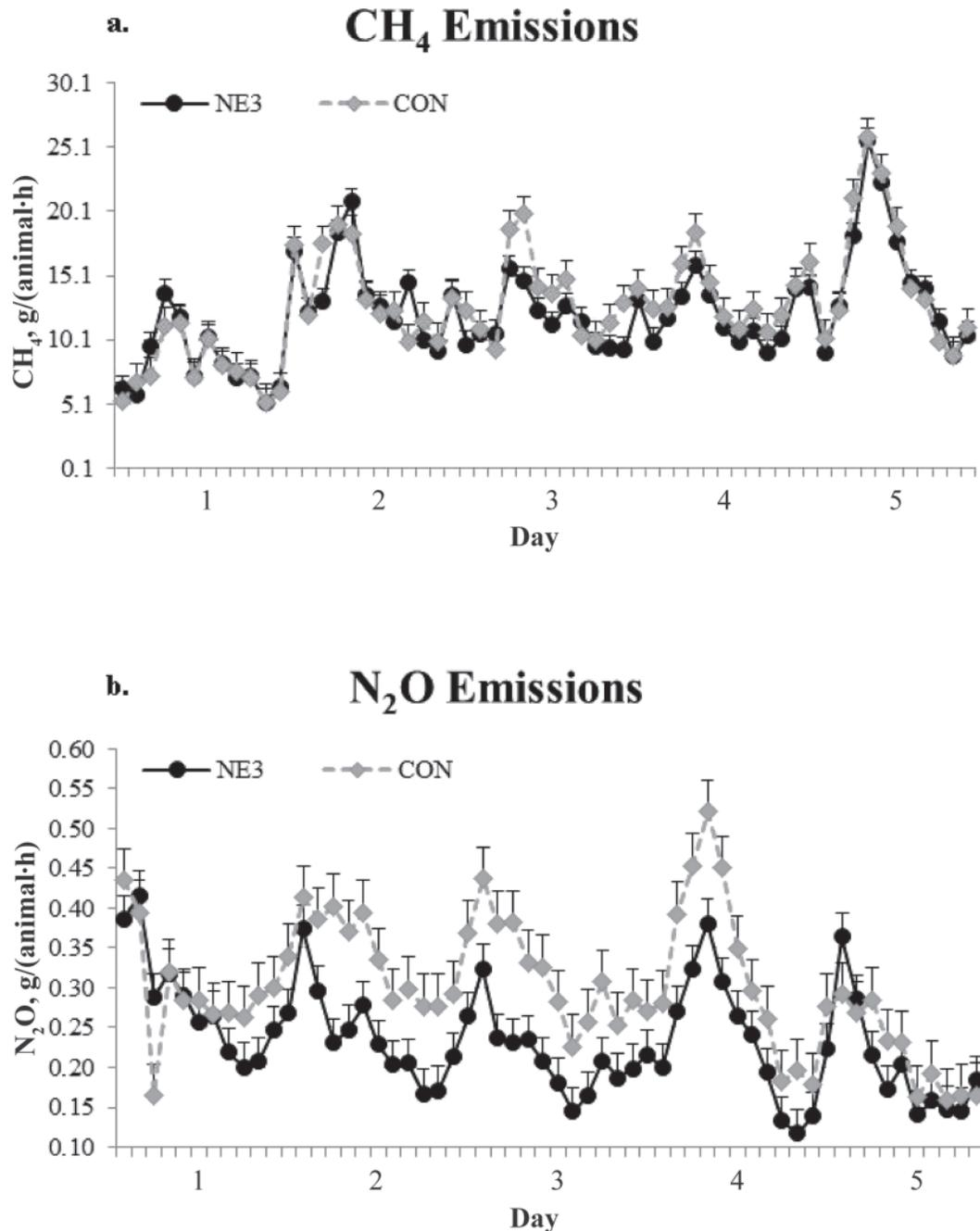


Figure 1. Average a) methane emission and b) nitrous oxide emission data from steers finished using Never Ever 3 (NE3) or conventional (CON) feedlot management for the 5-d experimental period cattle were housed in pen enclosures for emission recording. Error bars are SEM. Never Ever 3: no feed additives or implants. Conventional treatment: double implantation, ionophores, and ractopamine-HCl.

tically treat natural cattle. These cattle are costly to finish, but they can no longer be sold at the natural premium (Stovall and McCaffery, 2005).

Costs are also associated with the increased incidence of subclinical acidosis and resultant liver abscesses in the NE3 treatment group. Use of tylosin phosphate in feedlot rations has been reported to decrease the instance of liver abscesses by 40 to 70% (Nagaraja and Chengappa, 1998). Decreased performance effects have also been associated with abscessed livers, although there is considerable variation in the severity of these effects (Nagaraja and Lechtenberg, 2007). Carcasses with

condemned livers often have adhesions to surrounding organs or the diaphragm, which necessitates carcass trimming and a further decrease in saleable product. Other costs not accounted for in the current study include additional yardage costs associated with the longer DOF and the opportunity cost associated with the slower turnover rate of cattle in the feedlot. Additional expense would also be associated with sourcing verified natural stocker cattle. A recent cost study from California put this premium at \$0.05/kg for 240-kg calves, and \$0.15/kg for 347-kg natural feeder cattle (Nader et al., 2010).

Table 5. Averages (SEM) of ADG, DMI, daily methane and nitrous oxide emissions recorded during a 5-d period in the cattle pen enclosures (expressed on a per animal per day basis), and CO₂-eq¹ from methane (CH₄) kg/kg of feedlot BW gain of steers finished under Never Ever 3² (NE3) and conventional³ (CON) feedlot management systems; and predicted emissions based on COWPOLL and MOLLY mechanistic models as described by Kebreab et al. (2008)

Item	NE3	CON	P-value
Observed methane and nitrous oxide emissions			
ADG, kg/d (during measurement period)	1.28 (0.10)	1.70 (0.11)	0.008
DMI, kg/d (during measurement period) ⁴	8.56 (0.18)	9.93 (0.18)	0.0001
CH ₄ , g/(steer·d)	281.79 (20.02)	294.58 (10.57)	0.62
N ₂ O, g/(steer·d)	4.79 (1.79)	5.73 (0.89)	0.7
CO ₂ -eq from CH ₄ kg/kg of feedlot BW gain	5.02	3.92	—
Predicted methane emissions based on COWPOLL model			
GE, MJ/d	162	175	—
DE, MJ/d	121	131	—
CH ₄ , MJ/steer·d	7.00	7.62	—
CH ₄ , g/steer·d	136.23	148.29	—
Predicted methane emissions based on MOLLY model			
CH ₄ , MJ/(steer·d)	6.46	7.01	—
CH ₄ , g/(steer·d)	125.6	136.4	—

¹CO₂-eq: carbon dioxide equivalents in terms of global warming potentials (CO₂ = 1, CH₄ = 23).

²Never Ever 3: no feed additives or implants.

³Conventional treatment: double implantation, ionophores, and ractopamine-HCl.

⁴DMI during measurement period was used to adjust emissions. This value was greater than the overall DMI for the entire study.

The CON cattle had decreased marbling scores and a greater percentage (16% CON vs. 4% NE3) of select carcasses. Depending upon the Choice:Select spread, this would generally increase the value of the NE3 carcasses that graded 85% Choice, and 11% Prime. However, the NE3 carcasses that were yield grade 4 and 5 would likely incur a penalty in the order of \$0.22/kg of HCW. As mentioned previously, in commercial settings it is likely that the NE3 groups would have been finished at a lighter BW. Several studies have reported an effect of implants on quality grade. Guiroy et al. (2002) found that implanted steers graded low Choice or greater 46.3 to 56.8% of the time depending upon the implant strategy used, whereas control steers graded low Choice or greater an average of 62.5% of the time. Synovex Choice was chosen as the implant for the current study because it has been associated with more favorable quality grades than other anabolic implants (Prouty and Larson, 2010). The BAA RAC was likewise selected over the more aggressive zilpaterol hydrochloride because of the decreased quality grades that have been associated with the latter BAA (Strydom et al., 2009). In general, studies comparing RAC response in implanted cattle have found enhancement in feedlot performance and negligible effects on carcass quality (Gruber et al., 2007; Winterholler et al., 2007).

Few published cost studies compare natural and conventional feedlot management practices (Fernandez and Woodward, 1999; Berthiaume et al., 2006; Wileman et al., 2009); however, there are several extension reports available online (Baker, 2004; Anderson and Schoonmaker, 2005; Stovall and McCaffery, 2005; Acevedo et al., 2006). Using some of the cost estimates in these reports and the results of this study, the cost of procur-

ing the 337 kg natural stocker steers used in this study would require a \$56.55 premium (Nader et al., 2010), the cost of the additional 350 kg of DM of feed required to finish the natural cattle would amount to \$73.37, and the additional 42 d of yardage at \$0.30/d (Wileman et al., 2009) would total to \$12.60. Therefore, the natural premium would need to be at least the sum of these costs (i.e., \$142.52 per animal, \$0.24/kg of BW, or \$0.39/kg of HCW) to cover the additional expenses associated with producing a NE3 carcass.

Environmental Implications

Enteric fermentation processes associated with the digestion of plant material in ruminants cause the production of end products such as VFA, H₂, CH₄, NH₃, and CO₂. Globally, ruminant livestock produce ~80 million tonnes of CH₄ annually, accounting for ~33% of anthropogenic emissions of CH₄ (Beauchemin et al., 2008). Although several studies have performed life cycle analyses of GHG emissions from cattle production systems using standard emission figures typically derived from the Intergovernmental Panel on Climate Change (IPCC), few have measured actual emissions. The diurnal pattern of CH₄ observed in this study is the result of decreased activity and rumination during the night and has been observed in other studies as well (Hamilton et al., 2010). The increase in CH₄ production over the 5-d emission measurement period was likely partly attributable to CH₄ derived from the accumulating manure in the CPE. Kinsman et al. (1995) found that gas emissions from manure deposited in an environmental chamber contributed 5.8% to measured CH₄ output.

Table 6. Comparisons of studies that directly measured methane emissions from feedlot beef cattle fed a variety of diets

Diet	GE diet, MJ/kg of DM	DMI, kg/ (steer·d)	CH ₄ , g/ (steer·d)	CH ₄ , g/kg of DMI	CO ₂ -eq, kg/d	CO ₂ -eq, kg/kg of feedlot BW gain	Reference
NE3 ¹	18.63	8.6	281.8	32.7	6.48	5.02	Current study ²
CON ³	18.63	9.9	294.6	29.4	6.77	3.92	Current study ²
Corn backgrounding ⁴	18.31	10.23	254	24.8	5.84	4.87	(Beauchemin and McGinn, 2005)
Barley backgrounding ⁵	18.71	7.60	185	24.3	4.26	4.58	
Corn finishing ⁶	18.23	8.51	79	9.3	1.82	2.25	
Barley finishing ⁷	18.10	8.08	108	13.4	2.48	2.63	
Alfalfa/grass pasture	18.1	11.1	221.7	20.0	5.1	6.13	(Boadi, 2002)
Alfalfa/grass pasture + barley supplementation	—	12.9	236.5	18.3	5.4	4.89	
Low forage:grain	17.79	11.7	91.3	8.0	2.10	1.10	(Boadi, 2004)
High forage:grain	18.78	10.0	64.3	6.7	1.48	0.93	
Maize I ⁸	19.8	10.88	301	29.4	6.92	5.72	(Mc Geough et al., 2010a)
Maize II ⁸	19.0	11.95	304	25.8	6.99	5.17	
Maize III ⁸	18.9	11.13	301	27.7	6.92	5.55	
Maize IV ⁸	19.6	11.06	284	26.2	6.53	5.03	
ALC ⁹	19.7	11.03	228	22.1	5.24	3.60	
WCW silage I ¹⁰	18.9	10.3	295	30.1	6.79	8.27	(Mc Geough et al., 2010b)
WCW silage II ¹⁰	18.1	11.6	315	27.5	7.25	6.23	
WCW silage III ¹⁰	18.0	12.0	322	28.0	7.41	6.71	
WCW silage IV ¹⁰	18.2	10.7	273	25.9	6.28	6.02	
GS ¹¹	19.7	8.9	312	35.6	7.18	7.77	
ALC ¹²	19.7	10.4	180	15.3	4.14	3.10	
No additives ¹³	19.46	7.40	166.4	22.5	3.83	3.52	(McGinn et al., 2004)
Monensin ¹³	19.46	7.71	159.6	20.7	3.67	3.38	
Pellet ¹⁴	17.9	7.8	173.2	22.2	3.98	3.25 ¹⁵	(Reynolds and Tyrrell, 2000)
Dry rolled corn/silage	—	6.9	77.1	11.2	1.77	1.22	(Archibeque et al., 2007)
Barley grain (mean values)	17.8	11.3	179.6	15.9	4.13	2.89	(Hegarty et al., 2007)
Barley grain (minimum values)	17.8	5.87	84.4	14.4	1.94	2.55	
Barley grain (maximum values)	17.8	20.02	395.8	24.9	9.10	4.31	

¹Never Ever 3: no feed additives or implants.

²Data include methane emissions from manure deposited in cattle pen enclosure during the 5-d study period.

³Conventional treatment: double implantation, ionophores, and ractopamine-HCl.

⁴70% corn silage and 30% dry-rolled corn (DM basis).

⁵70% barley silage and 30% dry-rolled barley (DM basis).

⁶9% barley silage and 91% dry-rolled corn (DM basis).

⁷9% barley silage and 91% dry-rolled barley (DM basis).

⁸Maize silage harvested at various stages of maturity (I to IV), plus 2.57 kg concentrates (60% rolled barley, 33% soybean, 5% sugarcane molasses, and 2% mineral and vitamin premix, as fed).

⁹Ad libitum concentrates (83% rolled barley, 10% soybean, 5% sugarcane molasses, and 2% mineral and vitamin premix, as fed), plus 1.27 kg of grass silage (DM) daily.

¹⁰Whole-crop wheat silage of differing grain content (I to IV), plus 2.6 kg of concentrate DM (46% rolled barley, 46% soybean, 5% sugarcane molasses, 2% mineral and vitamin premix, and 1% vegetable oil, as fed).

¹¹Perennial rye grass silage, plus 2.6 kg of concentrate DM (46% rolled barley, 46% soybean, 5% sugarcane molasses, 2% mineral and vitamin premix, and 1% vegetable oil, as fed).

¹²Ad libitum concentrates (82% rolled barley, 10% soybean, 5% sugarcane molasses, 2% mineral and vitamin premix, and 1% vegetable oil, as fed), plus 1.28 kg of grass silage (DM) daily.

¹³Barley silage/barley grain diet.

¹⁴25% concentrate, 75% alfalfa pellet.

¹⁵BW gain calculated as difference between phase 1 and 3.

The daily CH₄ emissions per animal found in this study fell within the range that has been reported in other studies where CH₄ emissions have been measured in feedlot cattle (Table 6). As mentioned previously, values obtained in this study included both enteric CH₄

and CH₄ derived from the manure deposited in the CPE during the 5-d course of the experiment. The daily CH₄ emissions in Table 6 encompass a 6-fold range from a low of 79 g/d to a peak of 395.8 g/d. This highlights the importance of matching emission estimates to the attri-

butes of the production system because CH₄ emissions are dependent upon several factors including DMI, energy content of the feed, and ADG. The current study does not account for the emissions associated with the production of the extra feed consumed by the NE3 cattle during the feedlot finishing period, or for those associated with the additional waste generated during the extra 42 d on feed.

Nitrous oxide is derived from manure through nitrification and denitrification processes, which are influenced by air temperature and the amount of solids in the manure (Kebreab et al., 2006). Therefore, the N₂O emissions observed in the current study can be attributed to the cattle feces that were deposited in the CPE. A dairy cow study that examined N₂O in an environmental chamber found approximately 0.02 g/h or 0.48 g/d from the manure deposited by an animal in the chamber (Hamilton et al., 2010). The values observed in the current study were greater than this value due in part to the accumulation of manure throughout the entire time in the CPE (i.e., CPE were not cleaned on a daily basis during the course of the experiment).

Another method for evaluation of GHG emissions in livestock is through models that simulate emissions based on different factors, including feed intake, diet composition, and digestive processes. Mechanistic and empirical mathematical models allow for prediction of CH₄ based on dietary components without the costly equipment required to measure emissions directly from ruminants. Mechanistic models differ from empirical models that solely use nutrient intake to predict CH₄ emissions in that they predict emissions based on the actual biochemical fermentation processes in the rumen (Kebreab et al., 2008). Ellis et al. (2007) evaluated several empirical models and concluded that DMI and ME intake were the best dietary predictors for CH₄ production of the variables evaluated, with correlations to CH₄ production in beef animals of 0.44 and 0.36, respectively. Mathematical models have been found to be valuable predictors of CH₄ emissions; however, due to the large variability of beef diets there can be variation in the ability of a model to predict CH₄ emissions in beef cattle, which may explain the difference between the model and observed results for CH₄. The COWPOLL model performed best for predicting CH₄ emissions in dairy cattle, whereas the MOLLY model performed the best for feedlot cattle (Kebreab et al., 2008). In the current study, both COWPOLL and MOLLY underestimated the observed CH₄ emissions of both NE3 and CON cattle, although results from COWPOLL were closer to the observed values. However, some of the underestimation can be attributed to the models only approximating emissions arising from enteric fermentation, whereas observations were made on emissions arising from enteric fermentation and fresh manure.

The current study was not a life cycle assessment of GHG emissions. Several studies have looked at life cycle assessments of GHG emissions associated with red meat production (e.g., Haas et al., 2001; Casey and

Holden, 2006; Edwards-Jones et al., 2009; Beauchemin et al., 2010; Peters et al., 2010). Values of kg CO₂-eq/kg of HCW for beef range from 5.9 to 25.5 (Peters et al., 2010). A recent Canadian study assessing emissions from the whole beef production farming system (Beauchemin et al., 2010) most closely resembles the beef production system examined in this study. The authors estimated the GHG intensity of beef production to be 22 kg CO₂-eq/kg of HCW. They further approximated that within the beef production cycle, the extensive cow-calf sector accounted for about 80% of the emissions, and the intensive feedlot phase contributed approximately 20% of the emissions. In their simulation, approximately 4.4 kg CO₂-eq/kg of HCW was attributable to the feedlot phase of production, of which 2.9 kg was from enteric and feedlot manure CH₄ emissions. This aligns well with the current study, where these feedlot numbers were 2.69 and 3.37 kg CO₂-eq/kg of HCW for CON and NE3, respectively. Although the CON treatment reduced kg CO₂-eq/kg of feedlot gain by 28%, in reality this reduction would have a small effect on the total carbon footprint of beef production because the cow-calf system is the primary source of GHG emissions from beef production.

Social Implications

The social goals of sustainability are perhaps the most difficult to quantify. Product quality may be considered one attribute of social acceptability. Anabolic steroid use has been linked to decreased tenderness (Platter et al., 2003; Smith et al., 2007), and multiple implantations have been shown to increase WBSF values (Platter et al., 2003). Beta-agonists can also have variable effects on carcass tenderness, with RAC having less impact on tenderness than zilpaterol and clenbuterol (Strydom et al., 2009). Whereas WBSF values differed between treatment groups in the current study, the mean WBSF values for both the CON and NE3 cattle (3.6 kg for CON vs. 3.4 kg for NE3) were below the threshold value of 4.5 kg (Shackelford et al., 1991), above which consumers generally consider steaks to be tough. These low scores may be explained in part by the breed makeup (Angus-cross) of the steers and the 14-d aging period. Postmortem aging aids in the degradation of fibers and connective tissue, which contribute to meat tenderness; several studies have shown decreased WBSF values with postmortem aging (Platter et al., 2003; Stelzleni et al., 2008; Scramlin et al., 2010).

The association between the IGENITY Multibreed Panel (2008) marker scores and the target trait phenotypes were evaluated as a part of this study. There has been limited peer-reviewed research evaluating the association of these marker scores with their target trait. Van Eenennaam et al. (2007) reported a significant association of an earlier version of an IGENITY marker panel called *TenderGENE* with WBSF measurements and found a significant association of the test results with WBSF. The current study also found a signifi-

cant association of the IGENITY tenderness panel with WBSF values and an association between the marbling panel and marbling score. The DNA marker-assisted management may offer a management approach to help offset any negative product quality effects associated with the use of metabolic modifiers, although the economic feasibility of such an approach would need to be assessed.

Another aspect of social sustainability is consumer demand and willingness to pay an increased price due to the additional costs associated with producing NE3 product. Consumer demand is monitored by the National Cattlemen's Beef Association through scanner data at the retail level. For the 52 wk ending March 28, 2010, these scanner data indicated that natural and organic beef sales constituted 1.6% of all fresh beef sales in retail supermarkets, representing 2.5% of the total beef value (NCBA, 2010). According to the Agricultural Marketing Resource Center during the first quarter of 2010, prices for all beef products offered in retail supermarkets averaged \$7.54 per kilogram compared with natural and organic beef products, which averaged \$11.95 per kilogram, a premium of \$4.41 per kilogram (AMRC, 2010).

This suggests some consumers are willing to pay a significant premium for natural and organic meat products. The reasons why consumers are willing to pay this premium vary as elucidated in a survey of 1,288 Colorado consumers (Thilmany et al., 2006). Approximately 25% of those responding to the survey indicated a willingness to pay a premium for local, natural beef. Some were motivated by their perceptions of the premium quality of natural beef products. Others were concerned with production system attributes such as "no antibiotics," "no hormones," and "humane treatment." Some consumers may also be concerned about feedlot production systems in general, preferring less-intensive grass-raised beef systems. This broader production system analysis is beyond the scope of this study, but would be an interesting topic for future sustainability evaluations.

When asked to breakdown the reasons for their willingness to pay a premium for natural beef, on average 48% of the premium was based on perceived personal benefits (nutrition, quality, safety), 24% was based on public health concerns (potential antibiotic resistance, unknown hormonal effects), 23% was ascribed to broad societal benefits (support local agriculture, environmental benefits), and "other" concerns represented the remaining 5% of the premium. There were also consumers, especially lower income, price-conscious consumers, who were not willing or able to pay a premium for natural beef products. For those consumers "value for price" was an important issue because of comparatively less household income, and as a group they were less concerned about value-added product attributes including "natural" and "organic" claims.

Concerns about antibiotic and hormone-use may also stem from worries related to the excretion of these

products and their derivatives into the environment, and their retention in animal products. Several laboratory studies have documented abnormalities in endocrine function and reproduction in fishes exposed to trenbolone or estradiol metabolites (Kolok and Sellin, 2008), although it is unclear whether the use of implants increases the endocrine activity of cattle wastes in agricultural production systems. There are no studies that link hormone residues in meat or dairy products with adverse human health effects (CAST, 2005). The natural human production of both androgens and estrogens are several thousand times the content of a serving of beef produced with hormone implants. Likewise, other common foods are naturally much greater in estrogen than implanted beef, including eggs and milk. Soybean oil can contain as much as 9,000 times the estrogen activity as the same quantity of implanted beef (Preston, 1997). Regardless, these health and environmental concerns are contributing factors driving demand and creating an added-value market for natural beef.

Sustainability

It is unlikely that any one production system will ever satisfy all sustainability goals concurrently. Every production system has attributes that both support and act in opposition to the economic, social, and environmental goals of agriculture. Stern et al. (2005) illustrated this point by evaluating 3 model swine production systems: one that had an emphasis on maximizing environmental goals, one that had an emphasis on animal welfare goals, and one had an emphasis on product quality goals. They showed that with each production system there were sustainability benefits and drawbacks. Figure 2 illustrates the 2 feedlot management regimens examined in the study in the context of satisfying the sustainability goal triad.

Although some technologies are prohibited by agricultural production systems that are purported to be sustainable, technologies that work to improve efficiency and do not have a deleterious effect the environment are likely to have some sustainability benefits. To avoid favoring practices that satisfy sustainability goals at the expense of productivity, it is important to express comparisons in terms of a unit of output (Beauchemin et al., 2010; Place and Mitloehner, 2010). The environmental benefits associated with increasing the efficiency of production systems are often overlooked in sustainability discussions.

There have been significant gains in US beef cattle production efficiency over the past 50 yr. Output has almost doubled, whereas animal numbers have increased by only 3% from 93.35 million in 1958 to 96.03 million in 2008 (AMS, 1959; NASS, 2009). This has been achieved by employing management practices and technologies that improve productive efficiency, thereby reducing resource use and environmental impact per unit of output (Capper et al., 2009). Pretty (2008) suggested that agriculture needs a "sustainable intensifica-

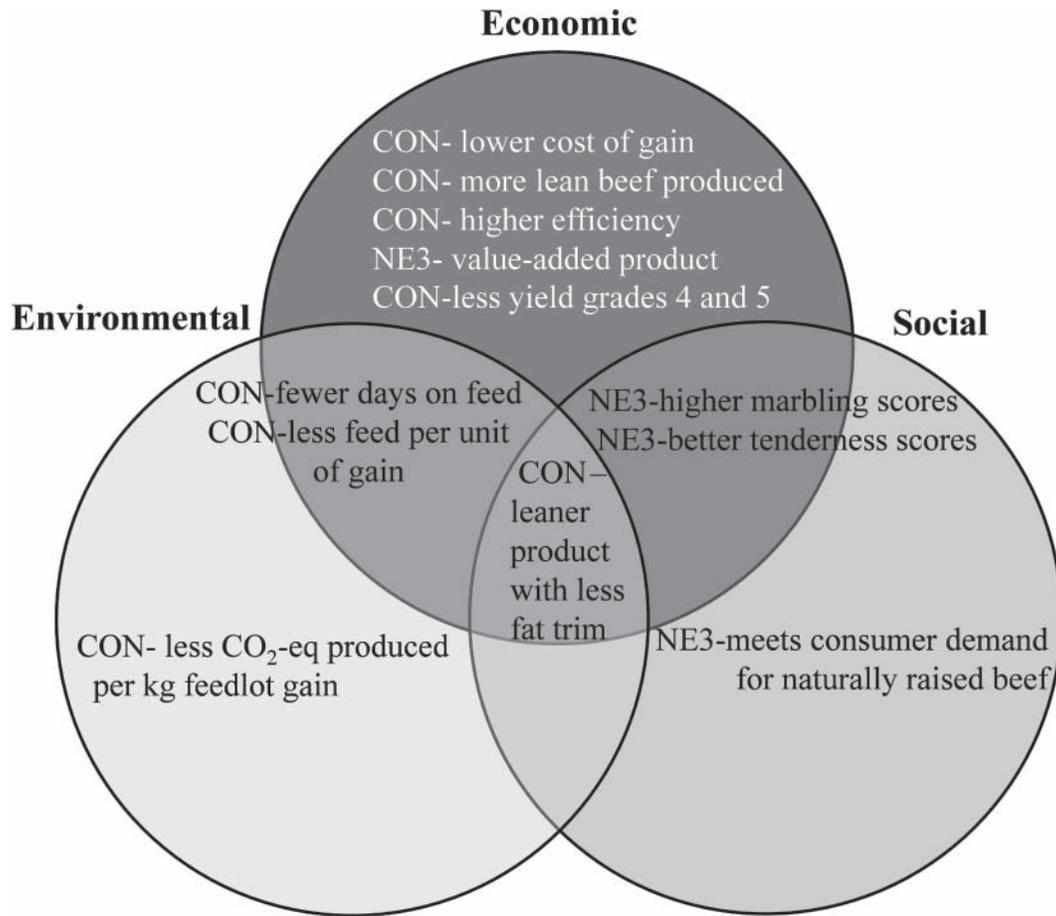


Figure 2. Venn diagram illustrating the sustainability benefits of Never Ever 3 (NE3) and conventional (CON) feedlot management systems. Never Ever 3: no feed additives or implants. Conventional treatment: double implantation, ionophores, and ractopamine-HCl.

tion” of existing resources and technologies, rather than a reduction of inputs, to move toward sustainability. He calls for producing more food from the same area of land while reducing the environmental impacts and issues a caution against any prejudice that limits the use of technological inputs on ideological grounds.

Conclusion

The metabolic modifiers used in the CON feedlot treatment resulted in positive economic (decreased cost of BW gain) and environmental (decreased feed use, fewer DOF, reduced CH₄ emissions) outcomes. The NE3 treatment met the specifications required to supply a process-verified program resulting in a high-value product outcome that meets the preferences of a defined consumer segment. Both feedlot management systems therefore satisfied some of the tripartite economic, environmental, and social goals of sustainability, but neither satisfied all 3 concurrently. The definition of what constitutes sustainable agricultural production practices will likely differ depending on the production environment, location, economic factors, and both the needs and values of individual consumers.

LITERATURE CITED

- Acevedo, N., J. D. Lawrence, and M. Smith. 2006. Organic, natural and grass-fed beef: Profitability and constraints to production in the Midwestern U.S. Accessed Dec. 28, 2010. http://www.agmrc.org/media/cms/organicnaturalgrassfedbeef_SADAA91F8FD74.doc.
- AMRC. 2010. Agricultural Marketing Resource Center. Natural Beef Profile. Accessed Dec. 28, 2010. http://www.agmrc.org/commodities_products/livestock/beef/natural_beef_profile.cfm.
- AMS. 1959. Farm Production, Disposition, and Income by States 1957–1958. Accessed Dec. 28, 2010. <http://usda.mannlib.cornell.edu/usda/nass/MeatAnimPr//1950s/1959/MeatAnimPr-04-00-1959.pdf>.
- AMS. 2009. Never Ever 3 (NE3). Accessed Dec. 28, 2010. <http://www.ams.usda.gov/AMSV1.0/getfile?dDocName=STELPRDC5066028>.
- Anderson, V. L., and J. P. Schoonmaker. 2005. Performance and carcass quality of finishing beef with natural feeding practices in North Dakota. Accessed Dec. 28, 2010. <http://www.ag.ndsu.edu/HettingerREC/beef/2005-sheep-beef-day-publication/EVALUATION%20OF%20PERFORMANCE%20AND%20CARCASS%20QUALITY%20OF%20FINISHING%20BEEF.pdf/view>.
- Archibeque, S. L., H. C. Freetly, N. A. Cole, and C. L. Ferrell. 2007. The influence of oscillating dietary protein concentrations on finishing cattle. II. Nutrient retention and ammonia emissions. *J. Anim. Sci.* 85:1496–1503.
- Arnot, C. 2008. Sustainability requires balance. *Feedstuffs* 80. April 28, 2008. The Miller Publishing Co., Minnetonka, MN.

- Baker, M. 2004. New York feedlot and carcass value discovery program—Final report. http://www.ansci.cornell.edu/beef/docs/feedlot_carcass_vdp_final.pdf. Accessed Dec. 27, 2010.
- Baldwin, R. L. 1995. *Modelling Ruminant Digestion and Metabolism*. Chapman & Hall, London, United Kingdom.
- Beauchemin, K. A., H. H. Janzen, S. M. Little, T. A. McAllister, and S. M. McGinn. 2010. Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study. *Agric. Syst.* 103:371–379.
- Beauchemin, K. A., M. Kreuzer, F. O'Mara, and T. A. McAllister. 2008. Nutritional management for enteric methane abatement: A review. *Aust. J. Exp. Agric.* 48:21–27.
- Beauchemin, K. A., and S. M. McGinn. 2005. Methane emissions from feedlot cattle fed barley or corn diets. *J. Anim. Sci.* 83:653–661.
- Berthiaume, R., I. Mandell, L. Faucitano, and C. Lafreniere. 2006. Comparison of alternative beef production systems based on forage finishing or grain-forage diets with or without growth promotants: 1. Feedlot performance, carcass quality, and production costs. *J. Anim. Sci.* 84:2168–2177.
- Boadi, D. A. 2002. Effects of grain supplementation on methane production of grazing steers using the sulphur (SF₆) tracer gas technique. *Can. J. Anim. Sci.* 82:151–157.
- Boadi, D. A. 2004. Effect of low and high forage diet on enteric and manure pack greenhouse gas emissions from a feedlot. *Can. J. Anim. Sci.* 84:445–453.
- Capper, J. L., R. A. Cady, and D. E. Bauman. 2009. The environmental impact of dairy production: 1944 compared with 2007. *J. Anim. Sci.* 87:2160–2167.
- Capper, J. L., E. Castaneda-Gutierrez, R. A. Cady, and D. E. Bauman. 2008. The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production. *Proc. Natl. Acad. Sci. USA* 105:9668–9673.
- Casey, J. W., and N. M. Holden. 2006. Greenhouse gas emissions from conventional, agri-environmental scheme, and organic Irish suckler-beef units. *J. Environ. Qual.* 35:231–239.
- CAST. 2005. Council for Agricultural Science and Technology. *Metabolic Modifiers for Use in Animal Production*. Issue Paper No. 30. CAST, Ames, Iowa. Accessed Dec. 28, 2010. http://www.cast-science.org/websiteUploads/publicationPDFs/metabolic_ip.pdf.
- Cederberg, C., and B. Mattsson. 2000. Life cycle assessment of milk production—A comparison of conventional and organic farming. *J. Clean. Prod.* 8:49–60.
- Dijkstra, J., H. D. S. C. Neal, D. E. Beever, and J. France. 1992. Simulation of nutrient digestion, absorption and outflow in the rumen—Model description. *J. Nutr.* 122:2239–2256.
- Edwards-Jones, G., K. Plassmann, and I. M. Harris. 2009. Carbon footprinting of lamb and beef production systems: Insights from an empirical analysis of farms in Wales, UK. *J. Agric. Sci.* 147:707–719.
- Ellis, J. L., E. Kebreab, N. E. Odongo, B. W. McBride, E. K. Okine, and J. France. 2007. Prediction of methane production from dairy and beef cattle. *J. Dairy Sci.* 90:3456–3466.
- Fernandez, M. I., and B. W. Woodward. 1999. Comparison of conventional and organic beef production systems I. feedlot performance and production costs. *Livest. Prod. Sci.* 61:213–223.
- Gruber, S., J. Tatum, T. Engle, M. Mitchell, S. Laudert, A. Schroeder, and W. Platter. 2007. Effects of ractopamine supplementation on growth performance and carcass characteristics of feedlot steers differing in biological type. *J. Anim. Sci.* 85:1809–1815.
- Guiroy, P., L. Tedeschi, D. Fox, and J. Hutcheson. 2002. The effects of implant strategy on finished body weight of beef cattle. *J. Anim. Sci.* 80:1791–1800.
- Haas, G., F. Wetterich, and U. Köpke. 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. *Agric. Ecosyst. Environ.* 83:43–53.
- Hamilton, S. W., E. J. DePeters, J. A. McGarvey, J. Lathrop, and F. M. Mitloehner. 2010. Greenhouse gas, animal performance, and bacterial population structure responses to dietary monensin fed to dairy cows. *J. Environ. Qual.* 39:106–114.
- Hegarty, R. S., J. P. Groopy, R. M. Herd, and B. McCorkell. 2007. Cattle selected for lower residual feed intake have reduced daily methane production. *J. Anim. Sci.* 85:1479–1486.
- IPCC. 2006 IPCC Guidelines for Greenhouse Gas Inventories, Vol. 4. 2006. Hayama, Japan, Institute for Global Environmental Strategies. Accessed Dec. 28, 2010. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf.
- Kebreab, E., K. Clark, C. Wagner-Riddle, and J. France. 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: A review. *Can. J. Anim. Sci.* 86:135–158.
- Kebreab, E., K. A. Johnson, S. L. Archibeque, D. Pape, and T. Wirth. 2008. Model for estimating enteric methane emissions from United States dairy and feedlot cattle. *J. Anim. Sci.* 86:2738–2748.
- Kinsman, R., F. D. Sauer, H. A. Jackson, and M. S. Wolynetz. 1995. Methane and carbon dioxide emissions from dairy cows in full lactation monitored over a six-month period. *J. Dairy Sci.* 78:2760–2766.
- Kolok, A. S., and M. K. Sellin. 2008. *The Environmental Impact of Growth-Promoting Compounds Employed by the United States Beef Cattle Industry: History, Current Knowledge, and Future Directions*. D. M. Whitacre, ed. *Rev. Environ. Contam. Toxicol.* 195:1–30. Springer, New York, NY.
- Mc Geough, E. J., P. O'Kiely, P. A. Foley, K. J. Hart, T. M. Boland, and D. A. Kenny. 2010a. Methane emissions, feed intake, and performance of finishing beef cattle offered maize silages harvested at 4 different stages of maturity. *J. Anim. Sci.* 88:1479–1491.
- Mc Geough, E. J., P. O'Kiely, K. J. Hart, A. P. Moloney, T. M. Boland, and D. A. Kenny. 2010b. Methane emissions, feed intake, performance, digestibility, and rumen fermentation of finishing beef cattle offered whole-crop wheat silages differing in grain content. *J. Anim. Sci.* 88:2703–2716.
- McGinn, S., K. Beauchemin, T. Coates, and D. Colombatto. 2004. Methane emissions from beef cattle: Effects of monensin, sunflower oil, enzymes, yeast, and fumaric acid. *J. Anim. Sci.* 82:3346–3356.
- Nader, G. A., L. C. Forero, J. K. McArthur, D. J. Drake, S. Larson, K. M. Klonsky, and R. L. De Moura. 2010. 2010 sample costs for beef cattle yearling/stocker production. Accessed Dec. 28, 2010. http://coststudies.ucdavis.edu/files/beefyearling_stockersv2010.pdf.
- Nagaraja, T. G., and M. Chengappa. 1998. Liver abscesses in feedlot cattle: A review. *J. Anim. Sci.* 76:287–298.
- Nagaraja, T. G., and K. F. Lechtenberg. 2007. Liver abscesses in feedlot cattle. *Vet. Clin. N. Am.- Food A.* 23:351–369.
- NASS. 2009. National Agricultural Statistics Service. *Meat Animals Production, Disposition, and Income 2008 Summary*. Accessed Dec. 28, 2010. <http://usda.mannlib.cornell.edu/usda/nass/MeatAnimPr/2000s/2009/MeatAnimPr-05-29-2009.pdf>.
- NCBA. 2010. National Cattlemen's Beef Association. *Natural/Organic Share of Total Beef*. Accessed Dec. 28, 2010. <http://www.beefretail.org/natural-organicshareoftotalbeefdollarandpound.aspx>.
- NEPA. 1970. The National Environmental Policy Act of 1969. Accessed Dec. 28, 2010. <http://ceq.hss.doe.gov/nepa/regis/nepa/nepaeqia.htm>.
- Peters, G. M., H. V. Rowley, S. Wiedemann, R. Tucker, M. D. Short, and M. Schulz. 2010. Red meat production in Australia: Life cycle assessment and comparison with overseas studies. *Environ. Sci. Technol.* 44:1327–1332.
- Place, S. E., and F. M. Mitloehner. 2010. Contemporary environmental issues: A review of the dairy industry's role in climate change and air quality and the potential of mitigation through improved production efficiency. *J. Dairy Sci.* 93:3407–3416.
- Platter, W. J., J. D. Tatum, K. E. Belk, J. A. Scanga, and G. C. Smith. 2003. Effects of repetitive use of hormonal implants on beef carcass quality, tenderness, and consumer ratings of beef palatability. *J. Anim. Sci.* 81:984–996.

- Preston, R. L. 1997. Rationale for the safety of implants. Pages 199–203 in *Symposium: Impact of Implants on Performance and Carcass Value of Beef Cattle*. F. Owens, D. Gill, G. Dolezal, B. Morgan, and G. Horn, ed. Okla. Agric. Exp. Sta., Div. Agric. Sci. Natural Res., Okla. State Univ., Stillwater.
- Pretty, J. 2008. Agricultural sustainability: Concepts, principles and evidence. *Philos. T. Roy. B* 363:447–465.
- Prouty, F., and E. Larson. 2010. Comparison of reimplantation strategies using Synovex Choice and Synovex Plus with Revalor-XS in feedlot steers. *Prof. Anim. Sci.* 26:76–81.
- R Development Core Team. 2009. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
- Reynolds, C. K., and H. F. Tyrrell. 2000. Energy metabolism in lactating beef heifers. *J. Anim. Sci.* 78:2696–2705.
- Scramlin, S. M., W. J. Platter, R. A. Gomez, W. T. Choat, F. K. McKeith, and J. Killefer. 2010. Comparative effects of ractopamine hydrochloride and zilpaterol hydrochloride on growth performance, carcass traits, and longissimus tenderness of finishing steers. *J. Anim. Sci.* 88:1823–1829.
- Shackelford, S. D., J. B. Morgan, J. W. Morgan, J. W. Savell, and H. R. Cross. 1991. Identification of threshold levels for Warner-Bratzler shear force in top loin steaks. *J. Muscle Foods* 2:289–296.
- Smith, K. R., S. Duckett, M. Azain, R. Sonon, and T. Pringle. 2007. The effect of anabolic implants on intramuscular lipid deposition in finished beef cattle. *J. Anim. Sci.* 85:430–440.
- Stelzlenti, A. M., D. D. Johnson, and T. A. Thrift. 2008. Effects of days on concentrate feed and postmortem aging on carcass and palatability of selected muscles from cull cows. *Prof. Anim. Sci.* 24:334–341.
- Stern, S., U. Sonesson, S. Gunnarsson, I. Oborn, K. I. Kumm, and T. Nybrant. 2005. Sustainable development of food production: A case study on scenarios for pig production. *Ambio* 34:402–407.
- Stovall, T., and J. McCaffery. 2005. Natural beef in the feedlot: Risk & return to feeder calf premiums. Range Beef Cow Symposium. Range Beef Cow Symposium. Animal Science Department, University of Nebraska, Lincoln. Accessed Dec. 28, 2010. <http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1049&context=rangebeefcowsymp>.
- Strydom, P. E., L. Frylinck, J. Montgomery, and M. Smith. 2009. The comparison of three beta-agonists for growth performance, carcass characteristics and meat quality of feedlot cattle. *Meat Sci.* 81:557–564.
- Thilmany, D. D., W. J. Umberger, and A. R. Ziehl. 2006. Strategic market planning for value-added natural beef products: A cluster analysis of Colorado consumers. *Renew. Agric. Food Syst.* 21:192–203.
- Thompson, P., and A. Nardone. 1999. Sustainable livestock production: Methodological and ethical challenges. *Livest. Prod. Sci.* 61:111–119.
- USDA. 2007. Sustainable Agriculture: Definition and Terms. U.S. Department of Agriculture. Accessed Dec. 28, 2010. <http://www.nal.usda.gov/afsic/pubs/terms/srb9902.shtml#toc2>.
- Van Eenennaam, A. L., J. Li, R. M. Thallman, R. L. Quaas, M. E. Dikeman, C. A. Gill, D. E. Franke, and A. G. Thomas. 2007. Validation of commercial DNA tests for quantitative beef quality traits. *J. Anim. Sci.* 85:891–900.
- Wileman, B. W., D. U. Thomson, C. D. Reinhardt, and D. G. Renter. 2009. Analysis of modern technologies commonly used in beef cattle production: Conventional beef production versus nonconventional production using meta-analysis. *J. Anim. Sci.* 87:3418–3426.
- Winterholler, S. J., G. Parsons, C. Reinhardt, J. Hutcheson, W. Nichols, D. Yates, R. Swingle, and B. Johnson. 2007. Response to ractopamine-hydrogen chloride is similar in yearling steers across days on feed. *J. Anim. Sci.* 85:413–419.
- Woodward, B. W., and M. I. Fernandez. 1999. Comparison of conventional and organic beef production systems II. Carcass characteristics. *Livest. Prod. Sci.* 61:225–231.

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