Evaluation of methane production manipulated by level of intake in growing cattle and corn oil in finishing cattle

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ABSTRACT: Growing crossbred steers [n = 80, initial body weight (BW) = 274 kg, SD = 21] were used to evaluate the effect of ad libitum and limit-fed intakes on methane (CH_4) production. Two treatments with four pens per treatment (10 steers per pen) were evaluated in a randomized block designed experiment, with BW as a blocking factor. Treatments included feeding the same diet at ad libitum intake or limit fed at 75% of ad libitum intakes. Diet consisted of 45% alfalfa, 30% sorghum silage, 22% modified distillers grains plus solubles, and supplement at 3% on a dry matter (DM) basis. This trial was followed by a finishing trial (n = 80; initial BW = 369 kg; SD = 25) to evaluate the effects of dietary corn oil on CH_4 production. Two treatments with four pens per treatment (10 steers per pen) were used in a randomized complete block designed experiment. Cattle were rerandomized and blocked by BW within the previous treatment. Treatments consisted of a control diet (CON) containing 66% corn, 15% wet distillers grains plus solubles, 15% corn silage, and 4% supplement (DM basis). Corn oil treatment (OIL) displaced 3% corn by adding corn oil. Methane was collected in two pen-scale chambers by collecting air samples continuously from pens by rotating every 6 min with an ambient sample taken between pen measurements. Steers fed ad libitum had greater DM intake (DMI) by design and greater average daily gain (ADG; $P < 0.01$) compared to limit-fed cattle; however, feed efficiency was not different between treatments (P = 0.40). Cattle fed ad libitum produced 156 g/d of CH_4, which was greater ($P < 0.01$) than limit-fed cattle (126 g per steer daily). In the finishing trial, BW, gains, and carcass traits were not impacted by treatment ($P \geq 0.14$). Feed efficiency (P = 0.02) improved because intakes decreased (P = 0.02) by feeding OIL compared to CON. Daily CH_4 production was less (P = 0.03) for OIL-fed cattle (115 g per steer daily) compared to CON-fed cattle (132 g per steer daily). Methane was reduced ($P < 0.01$) by 17% for OIL-fed cattle compared to CON-fed cattle when expressed as grams of CH_4 per kilogram of ADG. Feeding corn oil at 3% of diet DM reduced enteric CH_4 production (grams per day) by 15%, which was only partially explained by a 3% decrease in DMI. Overall, a decrease in CH_4 was observed when intake is limited in growing cattle and when corn oil is added in finishing diets.

Key words: beef cattle, corn oil, intake, methane

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INTRODUCTION

Methane (CH_4) production from ruminant animals has been a focus in research studies due to

environmental concerns associated with rising levels of greenhouse gases (GHG). Ruminants, and especially beef cattle, have received attention due to the amount of CH_4 they contribute to the global CH_4 budget. Ruminants contribute 17% of the global CH_4 production and beef cattle contribute 56% of total CH_4 from ruminants (Conrad et al., 2009; Tubiello et al., 2013). Environmental concerns are a main reason that mitigation strategies are being pursued in cattle production, but the energetic loss to the animal associated with CH_4 production is another reason for the research. Energy lost as a result of CH_4 production ranges from 2% to 12% with an average of 6% of energy intake lost due to CH_4 production (Johnson and Johnson, 1995).

One of the biggest determinants of CH_4 production is dry matter intake (DMI) by the animal. Diet digestibility and the subsequent volatile fatty acids (VFA) produced contribute to CH_4 production, but amount of feed intake plays a larger role in total CH_4 production. Methane production is largely dependent on the quantity of feed intake, although it can be altered by quality and digestibility (Blaxter and Clapperton, 1965). Forty-eight trials were examined by these authors, who found that CH_4 was increased as intake increased in all 48 instances.

Another strategy for CH_4 mitigation is through lipid supplementation. Hales et al. (2017) described three ways that dietary lipids reduce CH_4: 1) biohydrogenation of fatty acids, 2) increased propionate production from glycerol produced during lipolysis, which is then converted to propionate by anaerovibrio lipolytica bacteria, and 3) decrease in the available fermentable substrate in the rumen as fatty acids are not fermentable. Biohydrogenation converts unsaturated fatty acids to saturated fatty acids in the rumen, beginning with bacterial isomerase, which changes conformation from *cis*- to *trans*-fatty acids. Reductases then remove the double bond, forming a saturated fatty acid. Altering the lipid profile from unsaturated to saturated is energetically favorable, with an additional benefit of less toxicity for fiber-digesting bacteria in the rumen (Jenkins et al., 2007). Biohydrogenation in the rumen leads to a concomitant decrease in CH_4, as less hydrogen is available to methanogens. Biohydogenation is unable to compete at a high level with methanogens though as only 1% of metabolic hydrogens are used for biohydrogenation, while 48% are used to reduce carbon dioxide (CO_2) to CH_4 (Johnson and Johnson, 1995). Methanogens and protozoa struggle to survive in the presence of unsaturated fats, especially fats rich in lauric and myristic acids, which can lead to CH_4 decrease (Dohme et al., 2000). Feeding fats at an inclusion of 6% dietary dry matter (DM) has been shown to reduce CH_4 by 15%, but feeding in excess of 6–7% dietary DM as lipid can depress feed intake (Beauchemin et al., 2008; Patra, 2013). Patra (2013) observed that propionate increased with fat inclusion, probably due to less methanogens being present, allowing for a greater accumulation of hydrogens available for propionate production, as well as the conversion of glycerol to propionate through lipolysis. Overall, intake level is the main driver behind CH_4 production, and lipids are a viable mitigation option.

Objectives of these experiments were to 1) evaluate the impact of restricting intake on CH_4 production in growing cattle and 2) evaluate the effect of corn oil supplementation in finishing diets on CH_4 production, performance, and carcass characteristics. These authors hypothesized that limiting intake in growing diets and adding corn oil in finishing diets would decrease total CH_4 production while increasing feed efficiency [gain:feed (G:F)].

MATERIALS AND METHODS

All animal care and management practices were approved by the University of Nebraska-Lincoln Institutional Animal Care and Use Committee (approval number 1282).

Exp. 1: Growing Diets

A 105-d growing study was conducted at the Eastern Nebraska Research and Extension Center feedlot near Mead, NE. Eighty steer calves [initial body weight (BW) = 274 kg; SD = 21 kg] were utilized. Calves were received, weighed, and revaccinated against *infectious bovine rhinotracheitis*, bovine viral diarrhea types I and II, and parainfluenza type 3 (Bovi-Shield Gold 5, Zoetis Animal Health, Parsippany, NJ) and parasites (Dectomax, Zoetis Animal Health; (StandGuard, Elanco Animal Health, Greenfield, IN). Cattle were limit fed a common diet of 50% alfalfa and 50% Sweet Bran (Cargill Corn Milling, Blair, NE) at 2% of BW for 5 d (to equalize gut fill) and weighed for two consecutive days, then averaged, in order to obtain an accurate initial BW (Watson et al., 2013). Steers were blocked by BW (n = 3; block two has two replications), stratified within BW, and assigned randomly to pens. Pens were assigned randomly to treatment, with 10 steers per pen and 4 pens per treatment.

Treatments consisted of identical diets, either being fed ad libitum or limit fed. Diets were 45%

alfalfa, 30% sorghum silage, 22% modified distillers grains plus soluble (MDGS), and 3% supplement on a DM basis (Table 1). Supplement was formulated to provide 26 mg/kg of monensin (Rumensin, Elanco Animal Health). Limit-fed cattle received 75% of ad libitum cattle DMI from their respective replication within block from the previous week. On day 1, steers were implanted with 100 mg trenbolone acetate and 14 mg estradiol benzoate (Synovex Choice, Zoetis Animal Health). Ending BW was obtained after 5 d of limit feeding the same initial diet of 50% alfalfa and 50% Sweet Bran (Cargill Corn Milling, Blair NE) and collecting BW on two consecutive days. Ending BW measurements were decreased by 2.25 kg to account for weight gain while being limit fed [projected 5-d limit feeding diet results in 0.454 kg/d for average daily gain (ADG) of growing steers].

Two open-circuit indirect calorimeters were built by retrofitting a barn with two enclosed pens into the CH_4 barn at the Eastern Nebraska Research and Extension Center, near Mead, NE (Fig. 1). Each pen is 15.2-m long (east to west) × 13.3-m wide (north to south) with a 4.4-m wide alley running east to west on the north end of the pen. Two chambers share one central wall and a sliding alley door. Dividing walls between pens are hollow, wood-frame construction with a fabric liner and wood plank covering each side, which was beneficial for restricting air exchange between chambers. Doors in the south end of each pen are all garage doors (with 3.7- × 2.7-m maximum openings) that can be remotely opened and closed to facilitate the delivery of feed into bunks placed just inside the doorways. Doors are normally in closed position during trials and sealed with rubber tubing along the base of the door. Air leakage around these doors was considered a negligible concern since the objective was to have fresh air enter through openings in the south wall. Above each garage door is a gravity air inlet (two per pen; TJW Wall Inlets, QC Supply, Schuyler, NE) that is 111-cm long × 32-cm tall.

Table 1. Composition of diet (DM basis) for ad libitum and limit-fed cattle[a] (Exp. 1)

Ingredient	% of diet DM
Alfalfa	45
Sorghum silage	30
MDGS	22
Supplement[b]	
Fine ground corn	2.547
Tallow	0.075
Salt	0.300
Beef trace mineral[c]	0.050
Vitamin A–D–E[d]	0.015
Monensin premix[e]	0.013

[a]Limit fed = restricted to 75% of ad libitum cattle DMI.

[b]Supplement fed at 3% of diet DM.

[c]Premix contained 10% Mg, 6% Zn, 2.5% Mn, 0.5% Cu, 0.3% I, and 0.05% Co.

[d]Premix contained 1,500 IU of vitamin A, 3,000 IU of vitamin D, and 3.7 IU of vitamin E per gram.

[e]Formulated to supply monensin (Rumensin-90, Elanco Animal Health, Greenfield, IN) at 26 mg/kg.

Steers were rotated through these two pen-scale CH_4 chambers on a weekly schedule. Gravity inlets on the south wall of the building allowed air to enter chambers. Air is drawn through inlets using two fans on the north wall, creating a negative pressure system. Air is pulled through each pen and exits through the fans, with a sampling line positioned above the fans. Fans were calibrated twice, once prior and once after the trials (FANS System, Iowa State University). Airflow through the chambers with two fans running was 1,274 L/s. There are three separate sampling points, one within each pen and one outside of the south wall of the building to obtain ambient air samples. Air was sampled in each pen using a sampling line with a pump and controlled with a solenoid system and data logger. Solenoids switch sampling between the ambient line, pen 1, and pen 2, allowing for each pen to be sampled for 6 min. After cycling through the sampling of the two pens and ambient air, additional ambient air sample was collected for 2 min to complete a 20-min cycle.

A 2-min ambient sampling allows for easy recognition of when the cycle resets when data were being analyzed as pen 1 always follows the 2-min sampling period. Adequate time of 6 min allows for the system to be flushed between pen 1 and pen 2 sampling periods and provide ambient concentrations of CO_2 and CH_4.

Emissions data were averaged across each 6-min time point, excluding the first 30 s to avoid including lower measurements as gas acclimates to solenoid switching. Gas production per day was an average of all of the 6-min measurements per pen for a 24-h feeding period minus approximately 30 min at the time of feeding. Cattle were in the CH_4 barn for five consecutive days, then removed. Empty pens with manure accumulation were collected for 1 d, and then manure was removed and clean pens were measured for 1 d. With eight pens of cattle (four replications per treatment), and two pens in the CH_4 barn, the monitoring system allowed for cattle to enter the barn for one 5-d period every 4 wk. Each treatment

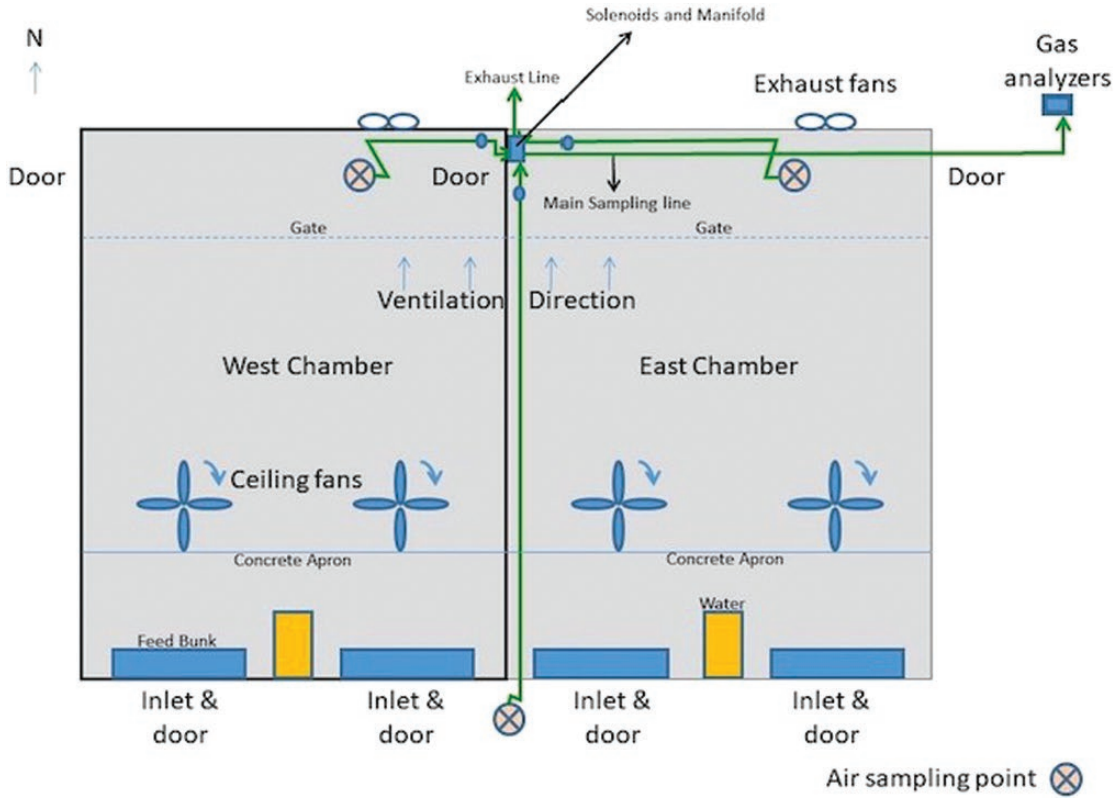

Figure 1. Methane barn side-by-side chamber and sampling system design.

was represented at all times in the CH_4 barn, as each block replication had emission collections at the same time. Each pen had three, 5-d collection periods throughout this trial, and pens were alternated between pen 1 and pen 2 with each rotation through the CH_4 barn. Gas measurement sampling errors on the first two collection periods made those data unusable. This error was a result of the CH_4 analyzer being saturated, as the upper limit for accurate measurements was 50 ppm and, at certain times throughout the day, this limit was exceeded. This problem was corrected for the third collection period by using two fans per pen instead of one, which moved air through at a faster rate and decreased CH_4 concentration in air samples. Only the third collection period emissions data are shown for Exp. 1.

Gasses were analyzed for CH_4 using a CH_4 analyzer (LI-7700 Open-Path CH_4 Analyzer) and CO_2 was measured using a different analyzer (LI-7500DS Open-Path CO_2/H_2O Analyzer; LI-COR Biosciences, Lincoln, NE). Methane analyzer operates using near-infrared laser and wavelength modulation spectrometry to detect the absorption of CH_4 in the air sample. The resolution of this instrument is 5 ppb root mean square at 10 Hz, in typical ambient concentrations (3 ppm CH_4). Measurement frequency of this analyzer is sub-MHz, meaning absorption can be detected at levels smaller than 10^{-5}. Carbon dioxide analyzer uses nondispersive infrared spectroscopy to measure CO_2 and water densities in the air sample.

Methane expressed per unit of intake (grams per kilogram of DMI) was calculated using the DMI across the 105-d growing period, as well as the DMI observed only while in the CH_4 chambers. Dry matter intakes were not different when fed in the outdoor pens compared to when in the chambers but were more variable because the duration was 5 d instead of 105 d. Methane and CO_2 emissions from manure were measured for 1 d after cattle completed their 5-d collection period. Measurements are from the accumulation of 5 d of manure building up in the chamber. Following 1 d of manure measurements, manure was removed and chambers were measured for another day to obtain a baseline level of emissions.

Data were analyzed using MIXED procedure of SAS as a generalized randomized block design with three blocks; blocks 1 and 3 had one replication, while block 2 had two replications. Pen was considered as an experimental unit and BW block was included in the model as a fixed effect. Using the R script to cleave the first 30 s of each 6-min sample resulted in 8.3% of data not being used.

Exp. 2: Finishing Diets

A 127-d finishing study was conducted at the Eastern Nebraska Research and Extension Center feedlot near Mead, NE. Crossbred steers (n = 80; initial BW = 369 kg; SD = 25 kg) were utilized. Cattle used in Exp. 1 were also used in Exp. 2 finishing trial. Cattle were limit fed a common diet of 50% alfalfa and 50% Sweet Bran (Cargill Corn Milling, Blair, NE) at 2% of BW for 5 d (to equalize gut fill) and weighed two consecutive days, then averaged, in order to obtain an accurate initial BW (Watson et al., 2013). Steers were blocked (n = 4) by BW and by previous treatment (ad libitum or limit fed), stratified within BW block, and assigned randomly to pens. Pens were assigned randomly to treatment with 10 steers per pen and 4 pens per treatment.

Control diet was 66% corn fed as a 50:50 blend of high-moisture corn (HMC) and dry-rolled corn (DRC), wet distillers grains plus solubles at 15%, corn silage at 15%, and supplement at 4% (DM basis). Treatment diet included 3% corn oil displacing 3% of HMC:DRC blend with the rest of the diet being similar to control (Table 2) Corn oil was sourced from E Energy Adams (Adams, NE) ethanol plant that extracted oil in the process of producing ethanol to mimic corn oil being fed in beef operations. Cattle were adapted to the finishing diet over a 24-d step-up period. Wet distillers grains plus solubles was held constant at 15%, while corn silage started at 81% and was displaced by HMC:DRC blend down to 15% over this period. Corn oil was introduced to the corn oil diet on day 18 of the step-up period and displaced 3% of corn silage. Supplement was formulated to provide 33 mg/kg of monensin (Rumensin, Elanco Animal Health) and 9.7 mg/kg of tylosin (Tylan, Elanco Animal Health) on a DM basis. Urea was added to both diets at 0.5% of diet DM to ensure that rumen degradable protein requirements were met. On day 1, cattle were implanted with 100 mg trenbolone acetate and 14 mg estradiol benzoate (Synovex Choice, Zoetis Animal Health). Steers were harvested on day 128 at Greater Omaha (Omaha, NE). Hot carcass weight was recorded during harvest, and a dressing percentage of 63% was used to calculate the final BW. Carcasses were chilled for 48 h and fat thickness, longissimus muscle (LM) area, and USDA marbling scores were recorded and yield grade was calculated.

The same pen-scale CH_4 calorimeter chamber described for Exp. 1 was used for this trial. Cattle were brought through the CH_4 barn for three periods, which lasted for 5 d of continuous collections each period. Each treatment was represented in the CH_4 barn at all times, as each blocks' replication entered at the same time, for a total of two pens being collected at the same time. Pens were alternated between pen 1 and pen 2 each time they entered for the sampling period to remove any bias from the CH_4 chambers. Feed refusals were removed from bunks once a week (at the end of each 5-d period) and weighed. A 59.9% diet DM was used to calculate dry feed refusals to correct intakes accordingly while the cattle were in the CH_4 barn. Methane and CO_2 emissions from manure were measured for 1 d after the cattle completed their 5-d collection period. Measurements are from the accumulation of 5 d of manure building up in the chamber. Following 1 d of manure measurements, manure was removed and chambers were measured for another day to obtain a baseline level of emissions.

Data were analyzed using MIXED procedure in SAS as a randomized complete block design with all blocks (n = 4) having one replication. Pen was an experimental unit and BW block was treated as a fixed effect. Gas production data were gathered over three periods, so data were analyzed using repeated measures using compound symmetry.

Table 2. Composition of diets for control versus corn oil treatments (Exp. 2)

Ingredient, % of diet DM	Control	Corn oil
DRC	33	31.5
High-moisture corn	33	31.5
Wet distillers grains plus solubles	15	15
Corn silage	15	15
Corn oil	–	3
Supplement[a]		
Fine ground corn	1.368	1.368
Limestone	1.640	1.640
Tallow	0.100	0.100
Urea	0.500	0.500
Salt	0.300	0.300
Beef trace mineral[b]	0.050	0.050
Vitamin A–D–E[c]	0.015	0.015
Monensin premix[d]	0.017	0.017
Tylosin premix[e]	0.011	0.011

[a]Supplement fed at 4% diet DM.

[b]Premix contained 10% Mg, 6% Zn, 2.5% Mn, 0.5% Cu, 0.3% I, and 0.05% Co.

[c]Premix contained 1,500 IU of vitamin A, 3,000 IU of vitamin D, and 3.7 IU of vitamin E per gram.

[d]Formulated to supply monensin (Rumensin-90, Elanco Animal Health, Greenfield, IN) at 33 mg/kg.

[e]Formulated to supply tylosin (Tylan-40, Elanco Animal Health) at 9.7 mg/kg.

Treatment, period, and block were included as fixed effects. Treatment by period interactions were tested for CH_4 production across time. Methane and CO_2 values were calculated the same as described in Exp. 1. Using the R script to cleave the first 30 s of each 6-min sample resulted in 8.3% of data not being used.

RESULTS AND DISCUSSION

Experiment 1

Performance. Dry matter intake and ADG were lower ($P < 0.01$) for limit-fed cattle compared to ad libitum cattle, while no difference ($P = 0.40$) was observed for feed efficiency (Table 3). Observing no difference in feed efficiency differs from what others have observed (Plegge 1987; Hicks et al. 1990). A 24% decrease in ADG observed in this trial is greater than 15% decrease reported by Murphy and Loerch (1994) when cattle were restricted to 80% of ad libitum intake. The 24% decrease observed in this trial is proportionate to the percentage of feed withheld from limit-fed cattle (25%), implying that, with every unit of feed withheld, no improvement in feed efficiency occurred. Mertens (1994) states that one of the most important aspects to forage quality in relation to animal performance is the level of intake. Improvements in feed efficiency that some authors have reported are likely from an increased diet digestibility, reduced animal movement, and a decrease in organ size as an animal is fed closer to maintenance requirements (Hicks et al., 1990). Most variation associated with DM digestibility (DMD) and digestible energy (DE) intake is associated with differences in intake level (60–90%), whereas only 10–40% is associated with the digestibility of feed (Mertens, 1994). Dry matter intake while in the CH_4 barn during the period was reduced ($P < 0.01$) for limit-fed cattle as well, consistent to when cattle were in outdoor pens. Ending BW was greater ($P < 0.01$) for ad libitum cattle compared to limit-fed cattle. The efficiency response observed in other trials related to limit feeding (Plegge, 1987; Hicks, 1990) was not observed in this trial. This could be due to not approaching maintenance levels as steers were still fed above maintenance.

Methane. Methane production (grams per day) was greater ($P < 0.01$) from ad libitum cattle compared to limit-fed cattle (Table 4). Ad libitum cattle produced 20% more CH_4 per day. Blaxter and Clapperton (1965) analyzed 48 sheep trials to determine the relationship between intake and CH_4 production and found that the total daily CH_4 produced increased with intake in each case. Beauchemin and McGinn (2006a) evaluated the effects of intake on CH_4 production in high-forage and high-concentrate diets and observed CH_4 production (grams per day) to be greater ($P < 0.01$) for ad libitum cattle compared to cattle restricted to 65% of ad libitum intake. In the present study, CH_4 production per kilogram per DMI over 105 d tended ($P = 0.07$) to be 8.0% lower for ad libitum compared to limit-fed cattle. Beauchemin and McGinn (2006a) reported that CH_4 production (grams per kilogram of DMI) was not different between ad libitum and limit-fed treatments. This is similar to what Blaxter and Clapperton (1965) observed for growing diets (low energy) when they reported that increasing feed amounts had no effect on CH_4 production as a percentage of intake. In finishing diets (high energy), these authors reported that, as feeding level increased, CH_4 as a percentage of intake is reduced. Johnson and Johnson (1995) found that, as feeding level increased, CH_4 lost as a percentage of gross

Table 3. Effects of ad libitum versus limit-feeding cattle on performance for growing diets (Exp. 1)

	Ad libitum	Limit fed[a]	SEM	*P*-value
Initial BW, kg	274	274	1	0.76
Ending BW, kg	380	354	2	<0.01
DMI, kg/d[b]	8.4	6.2	0.1	<0.01
DMI, kg/d[c]	8.4	6.5	0.2	<0.01
ADG, kg	1.01	0.77	0.02	<0.01
Gain:feed	0.121	0.125	0.002	0.40

[a]Limit fed = restricted to 75% of ad libitum cattle DMI.
[b]DMI over the 105-d trial.
[c]DMI while in the CH_4 barn during period 3.

Table 4. Effect of ad libitum versus limit-feeding cattle on CH_4 and CO_2 production for growing diets (Exp. 1)

	Ad libitum	Limit fed[a]	SEM	*P*-value
CH_4				
g/d	156	126	2	<0.01
g/kg of DMI[b]	18.7	20.3	0.4	0.07
g/kg of DMI[c]	18.7	19.5	0.8	0.53
g/kg of ADG[d]	155	164	7	0.41
CO_2				
g/d	6,831	6,032	163	0.04
g/kg of DMI[b]	818	974	22	0.02
g/kg of DMI[c]	816	937	45	0.16
g/kg of ADG[d]	6,765	7,856	346	0.11
CH_4:CO_2	0.023	0.021	0.0003	0.02

[a]Limit fed = restricted to 75% of ad libitum cattle DMI.
[b]DMI over the 105-d trial.
[c]DMI while in the CH_4 barn during period 3.
[d]ADG) over the 105-d trial.

energy intake (GEI) decreased by 1.6% for every unit of intake increase. The reason that Blaxter and Clapperton (1965) saw a difference in CH_4 production between low- and high-quality diets could be a result of passage rate and intake. Increasing intake of high-forage diets has less impact on passage rate than increasing intake on high-concentrate diets (Mathison et al., 1998). This could be a result of concentrates typically having smaller particle sizes to begin with, enabling passage rate to increase. Methane production per kilogram of DMI during the chamber measurement period was not different ($P = 0.53$) between ad libitum and limit-fed treatments. Methane per kilogram of ADG was not different ($P = 0.41$) between treatments. This would be expected after observing no improvement in efficiency for limit-fed cattle because the same diet was applied to both treatments. The proportionate decrease in CH_4 observed from limit feeding is a result of less fermentable substrate entering the rumen, leading to less fermentation and, therefore, less CH_4 production. Dry matter intake was restricted by 25% for limit-fed cattle and CH_4 (grams per day) was reduced ($P < 0.01$) by 19% compared to ad libitum treatment. This is similar to the conclusion made by Beauchemin and McGinn (2006a) when they reported that the decrease in CH_4 was proportional to the decrease in intake because, on a CH_4 grams per kilogram of DMI basis, there were no differences between treatments.

Carbon dioxide. Carbon dioxide (grams per day) was lower ($P = 0.04$) for limit-fed cattle compared to ad libitum cattle (Tables 3 and 4). Carbon dioxide (grams per kilogram of DMI) over 105-d growing trial was lower ($P = 0.02$) for limit-fed cattle compared to ad libitum cattle, but when analyzed relative to intake during the sampling period, CO_2 production was not different ($P = 0.16$). Carbon dioxide per kilogram of ADG was not different ($P = 0.11$) between treatments, although it was numerically 16% greater for limit-fed cattle compared to ad libitum cattle. The ratio of CH_4:CO_2 was lower ($P = 0.02$) for limit-fed cattle compared to ad libitum cattle. This implies that limit-fed cattle produced less CH_4 in proportion to CO_2 than ad libitum cattle, and it could be theorized that limit-fed cattle should have been more efficient because of it. This was not observed, as limit-fed cattle feed efficiency was not different from ad libitum cattle. Pesta et al. (2015) observed a decrease ($P < 0.01$) in CH_4:CO_2 between cattle on a low-quality forage diet with monensin present compared to without monensin. These same authors found no difference with the same treatments on a high-quality forage diet. The impact intake has on CH_4 production is well documented and understood, with these results confirming that the level of intake is a main mechanism driving variation in CH_4 production.

Manure. Methane from manure was 0.20 g/steer daily (SD = 0.25), while CO_2 was 114 g/steer daily (SD = 67). Murray et al. (1976) reported that 13% of CH_4 production comes from hindgut fermentation, while the rest is expired through lungs or eructation from the rumen. Of the 13% CH_4 produced in the hindgut, 89% is respired through lungs, leaving less than 1.5% of total emissions coming from the rectum as compared to the mouth. Results in this trial would suggest that less than 2% of daily CH_4 emissions are from manure. This could be a result of continuous CH_4 release from manure over the 5-d period, resulting in less volatiles being released on day 6 (during measurement period) than when first excreted from the animal. Cattle were not present while manure emissions were being measured. This results in manure being idle, which could also reduce emissions.

Baseline CO_2 levels were 325 g/steer daily when manure and cattle were removed from the chambers and were contributing to CO_2 measurements observed with manure and cattle in the chamber. Baseline CH_4 levels were 0.14 g/steer daily when manure and cattle were removed from the chamber, which contributed to CH_4 measurements reported with manure and cattle in the chamber. Emissions from manure were calculated by taking levels recorded with manure in the chamber and subtracting baseline levels recorded after manure removal from the chamber. Methane and CO_2 production from manure appears to be negligible but may be underestimated with these methods.

Experiment 2

Performance. Initial BW and final BW were not different ($P \geq 0.39$), while DMI was reduced ($P = 0.02$) for cattle fed 3% corn oil compared to control (Table 5). Pesta et al. (2015) reported that, when feeding corn oil at 3% of diet DM to steers on a finishing diet, no performance (DMI, ADG, and G:F) differences were detected relative to control. Hales et al. (2017) reported no DMI decrease ($P = 0.39$) when steers were fed corn oil at 0%, 2%, 4%, and 6% of diet DM displacing DRC. A decrease in DMI was expected because 6% corn oil treatment had a dietary lipid content of 9%, which exceeds recommended values of 6–7% (Beauchemin et al., 2008), but was not observed. Vander Pol et al. (2009) evaluated corn oil inclusion at 0%, 2.5%, or

Table 5. Effects of corn oil supplementation (3% of diet DM) in finishing diets on cattle performance and carcass characteristics (Exp. 2)

	Control	Corn oil	SEM	*P*-value
Performance				
Initial BW, kg	370	369	1	0.72
Final BW, kg	591	596	4	0.39
DMI, kg/d[a]	11.7	11.2	0.1	0.02
ADG, kg/d	1.74	1.80	0.02	0.14
G:F	0.150	0.161	0.003	0.02
Carcass characteristics				
HCW, kg	372	376	2	0.34
LM area, cm^2	82.0	84.2	1.1	0.27
Fat thickness, cm	1.44	1.39	0.07	0.60
Marbling score[b]	497	484	9	0.43
Calculated YG[c]	2.98	2.85	0.09	0.35

[a]DMI over the 127-d trial.

[b]Marbling score: 400 = Slight[00], 450 = Slight[50], 500 = Small[00], etc.

[c]Yield Grade (YG) = 2.50 + (0.9843 × rib fat thickness, cm) + (0.2 × 2.5% kidney, pelvic, and heart fat), + (0.0084 × hot carcass weight) − (0.0496 × LM area, cm^2; USDA, 2016).

5% of diet DM on finishing heifer performance and saw a tendency for reduced DMI of 10% for 5% corn oil treatment compared to control. These results are similar to the current study where DMI was reduced (P = 0.02) by 4% with corn oil supplementation. Gillis et al. (2004) reported no decrease (P = 0.23) in DMI when feeding 4% corn oil to heifers on a finishing diet. Burhoop (2017) tested adding 2% corn oil back to a diet with 30% deoiled MDGS and compared it to a control diet and a deoiled MDGS diet. This author observed that corn oil treatment resulted in heavier (P < 0.05) final BW compared to control and equal to deoiled MDGS treatment; however, DMI was reduced for 2% corn oil treatment compared to deoiled MDGS treatment (P < 0.05). Gillis et al. (2004) also reported no decrease (P = 0.23) in DMI when feeding 4% corn oil to heifers on a finishing diet.

In the present trial, corn oil did not affect (P = 0.14) ADG, although a numerical improvement of 3% was observed for corn oil treatment. A numerical increase in ADG could be in response to greater energy intake for cattle fed 3% corn oil. Vander Pol et al. (2009) reported that, as corn oil inclusion increased, ADG decreased linearly (P = 0.04). The tendency for reduced DMI could have offset additional energy in the diet from corn oil. In their study, dietary lipid content was 9% for 5% corn oil treatment, which exceeds the recommended limit for dietary lipids and could be affecting ADG as a result by possibly hindering fiber digestion. Gillis et al. (2004) did not see an ADG improvement (P = 0.23) when including corn oil at 4% of diet DM in a finishing diet. Similarly, Pavan et al. (2007) observed a tendency (P = 0.09) for ADG to improve as corn oil inclusion increased with grazing cattle. Bessa et al. (2005) reported that ADG was not impacted when 10% soybean oil was supplemented to lambs on both low- and high-concentrate diets. Gassman et al. (2002) reported that ADG was reduced (P < 0.05) for cattle fed 2.5% conjugated linoleic acid (CLA) compared to control in a corn-based finishing diet. This could be a result of lower DMI, which was reduced (P < 0.05) by 20% in CLA treatment.

Feed efficiency was improved (P = 0.02) by 7% for corn oil cattle over control cattle, which is expected as ADG was not different, but DMI was lower for corn oil cattle. Similarly, Burhoop (2017) reported an 11% improvement in G:F when supplementing corn oil at 2% of diet DM relative to control, but it could be a result of corn oil being fed in combination with MDGS. When compared to MDGS treatment without corn oil added, corn oil treatment had a 5% greater feed efficiency (P < 0.05). Vander Pol et al. (2009) reported that, as corn oil increased in the diet, a linear decline (P = 0.10) in feed efficiency occurred. These same authors tested corn oil at 3.4% diet DM versus a control diet containing predominantly DRC. These authors found a decrease in ruminal starch digestibility (P < 0.10) in corn oil diet, which could help explain the previous results where they concluded that corn oil linearly reduced feed efficiency in finishing heifers. Total starch digestion was numerically lower in their study for corn oil treatment and the authors concluded that supplemental oil may impede total tract starch digestion. Hales et al. (2017) found that starch digestibility was not impacted by corn oil inclusion.

Other oils apart from corn oil have been examined for their effects on feed efficiency. Beauchemin and McGinn (2006b) had similar findings as they showed that canola oil reduced (P < 0.01) intake, had no impact on ADG, and, therefore, had an 11% improvement in G:F compared to control. Similarly, Bessa et al. (2005) found that ADG did not differ when soybean oil was fed in a concentrate diet relative to control, but G:F was improved with oil inclusion when fed to lambs. Pavan et al. (2007) saw that, when corn oil was supplemented at 1.5 g/kg of BW to steers on tall fescue, G:F improved by 36% over control. Supplementing oil does not always lead to an improvement in feed efficiency. Gillis et al. (2004) fed corn oil to heifers and observed no differences in DMI, ADG, or G:F when

analyzed as the first 32 d on treatment or the last 28 d on treatment. Discrepancies between these results could be due to a number of things, including oil amount, type, form, and base diet composition.

All carcass characteristics were similar between treatments in this trial ($P \geq 0.27$; Table 5). These results are in agreement with what Gillis et al. (2004) reported for heifers fed corn oil in a finishing ration. These authors reported no differences between corn oil at 4% diet DM and control for hot carcass weight (HCW), LM area, marbling score, or fat thickness. Pesta et al. (2015) reported that carcass characteristics were not different for cattle fed 3% corn oil compared to control. Average daily gain was numerically greater for cattle fed 3% corn oil, but no differences were detected in HCW. This could be a result of cattle fed corn oil having numerically lower initial weights of 9 kg compared to control. Contrary to what was observed in the present trial, Vander Pol et al. (2009) reported that HCW were 7% lighter for cattle fed 5% corn oil, which could be a result of lower intake leading to lower gains. Burhoop (2017) reported a heavier HCW, as well as greater backfat, for corn oil cattle compared to control ($P < 0.05$), but no differences relative to MDGS treatment without corn oil added. This implies that the HCW difference reported between corn oil and MDGS treatment is largely due to MDGS rather than corn oil, although corn oil cattle were more efficient, which is similar to results observed in the present study. Pavan et al. (2007) reported some carcass parameter differences between control- and corn oil-supplemented steers that were finished on a forage-based tall fescue diet. These authors reported a linear improvement ($P = 0.01$) in HCW as corn oil inclusion increased from 0 to 0.75, to 1.5 g/kg BW. These differences can be attributed to replacing low-energy feed (fescue) with high-energy feed (corn oil). Overall, performance and carcass measures vary in response to corn oil (or other oil) supplementation. Discrepancies could be due to the effects of lipid on DMI and fiber digestion and subsequent performance impacts.

Methane. Methane production (grams per day) was reduced ($P = 0.03$) by 13% with the inclusion of corn oil relative to control diet (Table 6). This result could be from less fermentable feed entering from the rumen, lipids having a toxic effect on certain bacteria, or from biohydrogenation acting as a hydrogen sink (Beauchemin et al., 2007). Hales et al. (2017) is the only other study that has examined the effects of corn oil on CH_4 production in finishing beef cattle. These authors fed corn oil at inclusions of 0%, 2%, 4%, and 6% diet DM, displacing DRC. Methane was collected from eight steers using respiration chambers over a 24-h collection period. A treatment by sampling period interaction ($P = 0.02$) due to the magnitude of differences between OIL and CON across time was observed. This is likely an effect of DMI rather than CH_4 production as there was no CH_4 per kilogram of DMI treatment by sampling period interaction ($P = 0.32$). Methane (grams per day) was reduced linearly ($P < 0.01$) as the inclusion of corn oil increased. These same authors also reported a linear decrease ($P < 0.01$) in CH_4 as a percentage of GEI, with 6% corn oil reducing CH_4 by 34%. Of the three ways that lipids can reduce CH_4 that were previously discussed, these authors attributed the decrease in CH_4 to biohydrogenation. They concluded that, if displacing fermentable substrate with lipids were the reason, a decrease in VFA would have been observed but was not. Biohydrogenation is a hydrogen sink but typically only uses 1% of metabolic hydrogens available in the rumen, being out-competed by methanogens that use 48% of hydrogen (Johnson and Johnson, 1995). Beauchemin et al. (2008) reported that a 1% increase in supplemented lipid will reduce CH_4 (grams per kilogram of DMI) by 5.6%. Hales et al. (2017) showed that, for every 1% increase in supplemented lipid, CH_4 (grams per kilogram of DMI) was reduced by 4.5%. In the present trial, CH_4 (grams per kilogram of DMI) was reduced by 4.3% for every 1% increase in supplemented lipid.

When analyzing data as repeated measures, DMI, while in the CH_4 chambers, was not different between corn oil and control treatments ($P = 0.70$;

Table 6. Effects of corn oil supplementation (3% of diet DM) on CH_4 and CO_2 production from cattle fed finishing diets (Exp. 2)

				P-value	
	Control	Corn oil	SEM	TRT	Period
DMI, kg[b]	10.8	10.4	0.5	0.70	0.81
CH_4					
g/d	132	115	3	0.03	<0.01
g/kg DMI[a]	11.3	10.1	0.2	0.02	–
g/kg DMI[b]	12.8	11.1	0.9	0.29	0.56
g/ADG[c]	75.7	64.1	1.0	<0.01	–
CO_2					
g/d	10,907	10,538	252	0.38	0.31
g/kg DMI[a]	938	926	31	0.80	–
g/kg DMI[b]	1,072	1,016	83	0.67	0.43
g/ADG[c]	6,280	5,873	170	0.19	–
CH_4:CO_2	0.012	0.011	0.001	0.17	0.08

[a]DMI over the 127-d trial.

[b]DMI in the CH_4 barn across all three collection periods.

[c]ADG over the 127-d trial.

Table 5). The difference between treatments for DMI was consistent but, with only 5 d instead of 127 d, the differences were not detected for DMI while in the chambers. Methane production (grams per day) was impacted by period of measurement, and increased across time with days on feed ($P < 0.01$). Methane averaged across treatments were 116, 118, and 136 grams per steer daily for periods 1, 2, and 3, respectively (data not shown). There was not a treatment by period interaction for CH_4 production (grams per day; $P = 0.18$). Methane (grams per kilogram of DMI while in the chamber) was numerically lower, although not significant ($P = 0.29$) when corn oil was included compared to control as it was reduced by 13%.

Carbon dioxide. Carbon dioxide production (grams per day) was not different ($P = 0.38$) between corn oil and control treatments (Table 6). No other studies have reported the effect of corn oil on CO_2 production. The current study showed no differences in CO_2 production (grams per kilogram of DMI) between treatments ($P = 0.80$). Guyader et al. (2015) showed similar results as well, with no differences in CO_2 per kilogram of DMI when feeding linseed oil. In this experiment, CO_2 per kilogram of ADG was not different between treatments ($P = 0.19$). The ratio of CH_4:CO_2 was not different between corn oil and control treatment in this study ($P = 0.17$). When analyzed as repeated measures, CO_2 production (grams per day) did not differ between treatments over three sampling periods ($P = 0.38$; Table 6). Carbon dioxide per kilogram of DMI while in the CH_4 barn during the sampling periods was not different between treatments ($P = 0.67$), there was not a sampling period effect ($P = 0.43$), and no interaction between period and treatment occurred ($P = 0.55$).

Manure. Methane production from manure was 0.87 g/steer daily (SD = 1.12) and CO_2 from manure was 249 g/steer daily (SD = 173). Results are variable due to difficulties in removing all manure the same way between each collection period. Baseline CO_2 levels were 933 g/steer daily when manure and cattle were removed from the chambers and were contributing to CO_2 measurements observed with manure and cattle in the chamber. Baseline CH_4 levels are 1.9 g/steer daily when manure and cattle are removed from the chamber, which contributes to CH_4 measurements reported with manure and cattle in the chamber. Emissions from manure were calculated by taking levels recorded with manure in the chamber and subtracting baseline levels recorded after manure removal from the chamber. Baseline emission levels are greater than what was reported in Exp. 1 and could be a result of inconsistent manure removal between trials, as well as between periods within trial. A majority of the pen surface is soil, so it is difficult to remove all manure excreted by cattle or just manure without soil contamination. The amount of CH_4 and CO_2 produced from manure appears to be negligible but may be underestimated with these methods.

CONCLUSION

Total CH_4 production in growing cattle is largely dependent on the level of intake. When cattle were restricted to 75% of ad libitum intake, CH_4 (grams per day) and CO_2 (grams per day) were decreased relative to ad libitum cattle. These results were expected and gave further confidence that the CH_4 chamber system was detecting differences that would be expected with differing levels of intake. Adding corn oil in finishing diets decreased CH_4 (grams per day, grams per kilogram of DMI, and grams per kilogram of ADG), reduced intake, and improved feed efficiency while not affecting carcass characteristics. These results illustrate the impact of dietary oil on reducing CH_4 emissions while increasing efficiency in finishing cattle.

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