

Effect of low and high forage diet on enteric and manure pack greenhouse gas emissions from a feedlot

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Boadi, D. A., Wittenberg, K. M., Scott, S. L., Burton, D., Buckley, K., Small, J. A. and Ominski, K. H. 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. The objectives of this study were to assess enteric methane (CH₄) production by beef steers fed one of two isocaloric diets with different forage:grain ratios and to quantify greenhouse gas (GHG) emissions from bedded manure packs in the eight feedlot pens holding these steers (14 head pen⁻¹). Five animals (252 ± 20 kg) in each pen were randomly selected for measurement of CH₄ emissions over the course of the 126-d feeding trial. Two 24-h gas collections were completed for each steer in each of three collection periods using the sulfur hexafluoride tracer gas technique. The fluxes of nitrous oxide (N₂O), methane (CH₄) and carbon dioxide (CO₂) from bedding packs were measured using vented static chambers in each sampling period. Methane production (L d⁻¹) was 42% higher (*P* < 0.05) from steers fed the low forage:grain ratio than from steers fed the high forage:grain ratio. Overall, methane production (% of gross energy intake) ranged from 0.9 to 6.9% on the low forage:grain diet and from 0.7 to 4.9% on the high forage:grain diet. Daily CH₄ emissions were similar in the first two periods and increased during the third sampling period. There was no effect of diet on manure pack temperature during sampling, however, the manure pack was deeper (*P* < 0.05) in pens holding animals fed the high forage:grain diet. Furthermore, diet had no effect on the manure pack fluxes. Total daily non-CO₂ emissions from enteric and manure pack sources (CO₂ equivalent) were different (*P* < 0.05) between dietary treatments and averaged 1931 ± 81 g head⁻¹ d⁻¹ for the low forage:grain and 1394 ± 81 g head⁻¹ d⁻¹ for the high forage:grain diet.

Key words: Feedlot steers, greenhouse gases, enteric fermentation, manure packs

Boadi, D. A., Wittenberg, K. M., Scott, S. L., Burton, D., Buckley, K., Small, J. A. et Ominski, K. H. 2004. **Incidence d'une ration à faible ou à forte teneur en fourrage sur les émissions de gaz à effet de serre d'origine entérique et celles issues du fumier dans un parc d'engraissement.** *Can. J. Anim. Sci.* **84**: 445–453. L'étude devait servir à évaluer la production entérique de méthane (CH₄) par des bouvillons de boucherie recevant deux rations isocaloriques à rapport fourrage:grain différent ainsi qu'à déterminer le volume de gaz à effet de serre (GES) libérés par la litière accumulée dans les huit enclos où les animaux étaient gardés (14 sujets par enclos). Cinq animaux (252 ± 20 kg) ont été choisis au hasard dans chaque enclos et on a mesuré leurs émissions de CH₄ au cours des 126 jours de l'expérience. Pour chaque bouvillon, on a recueilli les gaz pendant 24 heures à deux reprises dans chacune de trois périodes en utilisant de l'hexafluorure de soufre comme traceur. Les flux d'oxyde nitreux (N₂O), de méthane (CH₄) et de dioxyde de carbone (CO₂) issus de la litière accumulée ont été mesurés au moyen de cellules aérées de manière statique durant chaque période d'échantillonnage. Les animaux nourris avec la ration à faible rapport fourrage:grain produisent 42 % plus (*P* < 0,05) de méthane (litres par jour) que ceux nourris avec l'autre ration. Dans l'ensemble, la production de méthane (pourcentage de la quantité d'énergie brute ingérée) varie de 0,9 à 6,9 % pour la ration à faible rapport fourrage:grain et de 0,7 à 4,9 % pour celle à ratio élevé. Les dégagements quotidiens de CH₄ étaient analogues au cours des deux premières périodes d'échantillonnage, mais plus élevés durant la troisième. La ration n'a eu aucune incidence sur la température de la litière accumulée durant l'échantillonnage, mais les enclos des animaux recevant la ration à rapport fourrage:grain élevé contenaient une quantité accrue de litière (*P* < 0,05). Par ailleurs, le régime n'a eu aucun effet sur les flux de la litière. Les émissions quotidiennes d'autres gaz que le CO₂ des sources entériques et de la litière accumulée (en équivalent CO₂) varient (*P* < 0,05) avec la ration et s'établissaient en moyenne à 1 931 ± 81 g par sujet et par jour pour la ration à faible rapport fourrage:grain et à 1 394 ± 81 g par sujet et par jour pour l'autre ration.

Mots clés: Bouvillons d'engrais, gaz à effet de serre, fermentation entérique, litière accumulée

The generation of GHG such as methane (CH₄) and nitrous oxide (N₂O) from the ruminant digestive tract and manure has been documented as a major contributor of atmospheric GHG emissions (Crutzen et al. 1986; Johnson and Ward 1996). In

2001, Canada's GHG emissions from enteric fermentation and manure management were 31.3 and 16.8%, respectively, of the total emissions from agriculture (Environmental Canada-GHG 1990–2001). Methane emissions from

Abbreviations: ADF, acid detergent fiber; ADG, average daily gain; BW, body weight; CP, crude protein; DMI, dry matter intake; ECD, electron capture detector; FID, flame ionization detector; GE, gross energy; GEI, gross energy intake; GHG, greenhouse gas; IVDMD, in vitro dry matter digestibility; IVOMD, in vitro organic matter digestibility; NDF, neutral detergent fiber; SF₆, sulfur hexafluoride; TCD, thermal conductivity

Canadian beef and dairy production account for 97% of total enteric fermentation emissions (Janzen et al. 1999). Current Canadian estimates for GHG emissions from feedlot animals and manure are based largely on average emission factors for CH₄ and N₂O derived from the Intergovernmental Panel on Climate Change (IPCC) guidelines (Neitzert et al. 1999). Differences in cattle management, feeding, and climatic conditions affecting animal and microbial populations in manure or bedding packs are expected to result in significant deviations between the IPCC estimates and actual GHG emissions from western Canadian feedlots. There is, therefore, the need to accurately quantify GHG emissions from feedlot operations that reflect the commercial production systems in western Canada.

Diet formulation influences the carbon:nitrogen ratio of excreted manure, which, in turn, can influence the extent of CH₄ released from manure. In general, lowering the carbon:nitrogen ratio leads to relatively higher CH₄ production under anaerobic conditions (Jarvis et al. 1995). On the other hand, cattle consuming high forage diets produce manure with a higher content of partially digested cell wall material, which is more resistant to microbial degradation and subsequent release of carbon as compared to cattle consuming high grain diets (Jarvis et al. 1995). Manure pack GHG emissions are influenced by several factors including diet formulation, amount and source of bedding, pack moisture level, and temperature.

The addition of fats to feedlot rations increases the energy density of diets, thereby allowing the incorporation of more forage and less grain into the diets without compromising diet energy density. Addition of fat and oils to ruminant diets also has been shown to depress CH₄ production through biohydrogenation of unsaturated fatty acids (Dong et al. 1997; Machmuller and Kreuzer 1999). The presence of undigested fat or oils in manure packs may influence microbial behavior during manure storage, but the consequences relative to GHG emissions are not known (Lodman et al. 1993; Gonzalez-Avalos and Ruiz-Suarez 2001).

The first objective of this study was to assess enteric CH₄ emissions by beef steers fed isocaloric diets with two ratios of forage:grain, through the inclusion of sunflower seeds as a fat source. The second objective was to quantify GHG emissions from bedded manure packs in pens of the same feedlot steers over a 126-d feeding period. Enteric and manure pack GHG emissions were used to calculate gross emissions for the two feedlot feeding strategies.

MATERIALS AND METHODS

Animals and Management

The experiment was conducted at the Agriculture and Agri-Food Canada Research Centre, Brandon, Manitoba. One hundred and twelve Continental × British crossbred steers (182 d of age) averaging 252 ± 27 kg (mean ± SD) were moved into a feedlot 2001 Oct. 02 to compare two diets with different forage:grain ratios on GHG emissions from animals and excreted manure. Animals were allowed 4 wk to adjust to their assigned diets before measurements began. Animals were evenly allocated (based on dam breed, previ-

ous pasture grazed, and calf weaning weight) into eight pens (14 animals per pen) and monitored for 126 d period for enteric and manure pack GHG emissions and to slaughter for steer performance. Greenhouse gas collection stopped after 126 d of feeding as some steers had reached target finish conditions (6 to 8 mm backfat) and were removed for slaughter resulting in low animal numbers in some pens. Feedlot pens were 685 m² with a bunk length of 19.5 m, which permitted all steers in each pen to consume feed at the same time. Pens received wheat straw bedding once a week, the amount allocated per pen held constant during the course of the 126-d study. Steers were managed according to the guidelines of the Canadian Council on Animal Care (1993).

Four pens of animals were assigned to an 83.5% steam-rolled barley grain diet, while the other four pens received an isocaloric diet containing 41.7% steam-rolled barley grain and 14.0% whole sunflower seed [dry matter (DM) basis, Table 1]. Whole-plant barley silage made up the forage component of the feedlot diets. Monensin was used in both diets (Table 1). Animals were fed once a day at 1600. Feed offered was adjusted daily so that bunks contained 5 to 10% orts (feed refused) after 16 h (0800) and 0% orts (slick-bunk) after 24 h (1600). Adjustments were made by reducing or increasing feed offered by 0.5 kg per animal. Daily feed offered and orts were recorded for each pen. Diet and ort samples were collected weekly for DM and chemical analyses. Fresh water was provided on an ad libitum basis.

Body weight measurements were taken before feeding every 14 d, and in 2 consecutive days at the start and end of the test period. Steers were given an implant of a progesterone:estradiol growth promotant (Synovex-S[®], Ayerst Veterinary Laboratories) initially and day 70 of the study. Backfat thickness was measured every 4 wk between the 12th and 13th rib using real-time ultrasonography (Aloka SSD500, 5.0 Mhz probe, Aloka Co. Ltd., Japan). Finished weight was taken the day before shipping, and after a 16-h withdrawal of feed (shrunk weight) just prior to shipping.

Enteric CH₄ Emissions

Forty steers (250 ± 20 kg, mean ± SD); five animals pen⁻¹ were randomly selected for measurement of CH₄ produced by enteric fermentation during the course of the feedlot trial. Gas sampling occurred in three periods designated Period 1 (Nov. 07–Dec. 19); Period 2 (Dec. 20–Feb. 13) and Period 3 (Feb. 14–Mar. 13) in the 2001–2002 winter season, to assess enteric emissions with growth of steers in the feedlot. Two 24-h gas collections were conducted from all 40 steers in each period. Enteric CH₄ gas production was measured using the sulfur hexafluoride (SF₆) tracer gas technique (Boadi et al. 2002), which allows the direct measurement of CH₄ production from individual animals in feedlot conditions.

Stainless steel permeation tubes containing SF₆ with known release rates (250–500 ng min⁻¹) as described by Boadi et al. (2002) were placed in the rumen (through the throat) using a speculum 1 wk prior to the first CH₄ gas collection. This allowed enough time for the tracer gas to equilibrate in the rumen. Animals were trained to wear the gas collection apparatuses during the equilibration period. Exhaled gas from the nose and mouth was drawn into pre-

Table 1. Ingredient and chemical composition (DM basis) of diets fed to steers in the feedlot

Ingredient	Low forage:grain diet	High forage:grain diet
Barley silage (%)	11.5	41.8
Barley grain (%)	83.5	41.7
Whole sunflower seed (%)	—	14.0
Soybean meal (%)	2.5	—
Mineral supplement (%) ^z	2.5	2.5
<i>Chemical composition (DM basis)</i>		
DM (%)	73.9	55.6
CP (%)	13.2	12.0
ADF (%)	10.2	18.5
NDF (%)	19.6	29.1
EE (%)	2.2	8.3
Ash (%)	4.78	7.23
Ca (%)	0.49	0.69
P (%)	0.44	0.43
IVOMD (%)	80.6	70.7
GE (kJ g ⁻¹)	17.79	18.78

^zMineral supplement contains (as fed basis): crude protein, 15%; calcium, 24%; salt, 10%; sulfur, 1%; copper, 0.6 g kg⁻¹; manganese, 1.2 g kg⁻¹; zinc, 2.4 g kg⁻¹; Monensin, 1.2 g kg⁻¹; selenium, 6 mg kg⁻¹; iodine, 30 mg kg⁻¹; cobalt, 10 mg kg⁻¹; vitamin A, 200 KIU kg⁻¹; vitamin D, 12 KIU kg⁻¹; vitamin E 3500 IU kg⁻¹.

evacuated (30 mm Hg) stainless steel collection canisters (130-mm diameter) through 900-mm capillary tubing (128 µm i.d.) with an in-line 15-µm filter and flexible nose piece fitted to a halter (Boadi et al. 2002). Similar collection apparatuses were positioned on the east and west sides of pen posts to monitor daily background air samples, which were used to correct expired gas concentrations. Following a 24-h period of collection, canisters were removed and pressure tested to identify blocked or leaking capillary systems. Thereafter, canisters were pressurized to 110 KPa with pure N₂ to prevent sample contamination prior to analyses and to allow injection of gas samples into the sample loop of a gas chromatograph.

Manure Pack GHG Emissions

Nitrous oxide, CH₄, and CO₂ emissions from manure packs in each pen were measured once per period. The flux of N₂O, CH₄, and CO₂ was measured using vented static chambers (Hutchinson and Livingston 2002). Six two-piece chambers, consisting of a 20.3-cm-diameter × 15-cm-high collar fitted with a 20.3-cm-diameter lid, which contained a vent tube and port fitted with a rubber stopper to allow sample removal, were used in each pen during each period. Collars, which were inserted into the manure pack to a depth of 7.5 cm, were embedded in a diagonal transect across the bedding pack to reflect changes in depth and composition of manure packs in the pen. Gas flux measurements were taken by securing the lid on the collar using elastic bands and collecting samples of the head space at 0, 5, and 60 min following closure. Gas accumulation during an initial 5-min period was used to calculate CO₂ flux and during a 60-min period for N₂O and CH₄ flux. At each time period, 15 mL of atmosphere was collected from the headspace of the chamber using a 20 mL disposable syringe (Becton-Dickinson), and injected into a 10 mL evacuated glass tube (Becton-

Dickinson) and sealed with silicone sealant. Tubes were flushed with Helium and evacuated to a vacuum of < 0.5 Torr prior to use. Five replicates of 15 mL from two standard gas mixtures (high standard containing 658 ppmv N₂O, 1036 ppmv CO₂, 9.2 ppmv CH₄; low standard containing 283 ppmv N₂O, 196 ppmv CO₂, 4.4 ppmv CH₄) were also injected into evacuated tubes and handled in a similar manner as the experimental tubes. Tubes were transported to the laboratory for immediate analysis.

Manure pack temperature along the same diagonal transect was recorded simultaneously to gas flux measurements using a hand-held thermometer inserted to a depth of 10 cm in each chamber. Manure pack depth (at three locations of the chambers) and area were estimated in each pen for each sampling period. Manure pack depth was measured using a sharpened steel rod that was pushed into manure pack to the frozen soil. Approximately 20 samples of manure pack were taken to soil level, along the same diagonal transect around the chambers using a core sampler. Core samples were composited and frozen (-20°C) until subsequent analysis for DM, C, and N were performed.

Intake Estimation

Individual DM intake of the 40 steers was determined using chromic oxide coupled with an estimation of in vitro DM digestibility (Minson 1990). Fecal output was estimated using chromic oxide controlled release capsules (1.42 g Cr₂O₃ d⁻¹; Captec Chrome Ltd, NZ) which were placed in the rumen of the steers 7 d prior to each CH₄ sampling period. A fecal grab sample was taken from each animal during each CH₄ collection in each period to correlate DM intake to CH₄ emissions. In vitro DM digestibility (Tilley and Terry 1963) was conducted on diet samples composited from the weekly samples taken in each period.

Gas Analysis

A gas chromatograph (Star 3600, Varian, Mississauga, ON) fitted with an electron capture detector (ECD) to measure SF₆, and a flame ionization detector (FID) to measure CH₄ and CO₂ concentrations in gas samples collected from steers was used (Boadi et al. 2002). Gas concentrations (SF₆ and CH₄) were determined from peak areas and identified from their different retention times relative to the known standards. Daily CH₄ production was calculated as follows:

$$\text{CH}_4 \text{ (L min}^{-1}\text{)} = \frac{\text{permeation tube SF}_6 \text{ release rate}}{(\text{L min}^{-1}) \times [\text{CH}_4]/[\text{SF}_6]}$$

where [CH₄] and [SF₆] are the concentrations of CH₄ and SF₆ in canisters after background concentrations have been deducted.

Manure pack samples were analyzed using a Varian Star 3800 Gas Chromatograph (Varian, Mississauga, ON) fitted with ECD, FID, and thermal conductivity (TCD) detectors and with a Combi-PAL autosampler. A 2.5-mL volume was removed from the sample tube via the autosampler and injected into a sample valve that delivered 0.25 mL to the ECD and 0.25 mL to the TCD and FID in series. For N₂O measurements, the system was configured with a 0.3 m Poropak Q

backflush column followed by a 1.8 m (3.2 mm i.d.) Poropak QS analytical column (Supelco, Bellefonte, PA). The carrier gas was Ar/CH₄ (90:10 ratio), maintained at a flow rate of 30 mL min⁻¹ (head pressure of 13 psi). The injector was set at 100°C, the columns at 70°C, and the ECD at 300°C. Methane and CO₂ analysis were carried out using a 0.3 m Poropak N (3.2 mm i.d.) and a 1.8 m Haysep D (3.2 mm i.d., 80/100 mesh) analytical columns (Chromatographic Specialties Inc., Brockville, ON). Helium carrier gas was delivered at a rate of 80 mL min⁻¹ (head pressure of 20 psi). Air and hydrogen gas flow to the FID were 300 mL min⁻¹ and 30 mL min⁻¹, respectively. Temperature of the column oven, FID, and TCD were 70, 250, and 130°C, respectively. Five replicates of two concentrations of standard gas mixtures (same concentrations as those used during sampling) were included in each run and were used to construct standard curves. The standard gases collected during sampling were used to confirm sample integrity during sampling and storage. Flux was calculated as the change in the amount of gas contained in the head space as a function of time and expressed per unit area based on the area enclosed by the chamber.

Chemical Analyses

Feed, fecal, and bedding samples were dried for 48 h in a forced-draught oven at 60°C for DM determination. Samples were ground using a Wiley Mill fitted with a 1-mm screen. Dried feed samples were analyzed for crude protein (CP) using a Kjeltac 1030 auto analyzer [Tecator Inc., Herndon, VI; Association of Official Analytical Chemists (AOAC) 1990, method no. 984.13], and ash, (method no. 942.05, AOAC 1990). Acid detergent fiber (ADF) and neutral detergent fiber (NDF) were determined using an ANKOM 200 fiber analyzer (Fairport, NY), as described by Komarek (1993). Gross energy (GE) was determined using a Parr 1241 adiabatic bomb calorimeter. Chromium concentration in fecal samples was determined by atomic absorption spectrophotometry (Model IL 551 AA/AE spectrophotometer), using air and an acetylene flame (William et al. 1962).

Statistical Analysis

Performance data [average daily gain (ADG), dry matter intake (DMI), FG, days on feed], animal and manure bedding greenhouse gas production data were analyzed by analyses of variance using GLM of SAS Institute, Inc. (1990). Enteric emissions and total emissions per pen were analyzed using a split plot design in the Proc Mixed procedure in SAS software. The following are the models used:

Animal performance: $Y_{ij} = \mu + D_i + \epsilon_{ij}$

Animal performance (during 126 d) data:

$$Y_{ijk} = \mu + D_i + P_j + DP_{ij} + \epsilon_{ijk}$$

Animal CH₄ production data:

$$Y_{ijk} = \mu + D_i + P_k + DP_{ik} + A(D)_{ij} + \epsilon_{ijk}$$

Pen basis data: $Y_{ijk} = \mu + D_i + P_k + DP_{ik} + PN(D)_{ij} + \epsilon_{ijk}$

Where Y_{ij} and Y_{ijk} = traits under consideration; μ = overall mean; D_i = diets ($i = 1, 2$); P_j and P_k = period ($j = 1..3$); DP_{ij} = diet \times period interaction; $A(D)_{ij}$ = animal effect nested within diet; $PN(D)_{ij}$ = pen effect nested within diet; ϵ_{ij} and ϵ_{ijk} = experimental error term. Means were separated at the 5% level of significance using the probability of differences (PDIFF) options. One animal suffered a hip injury and was removed from the study.

RESULTS AND DISCUSSION

Feedlot Growth Performance

Addition of whole sunflower seeds containing 432 g fat kg⁻¹ DM allowed a partial replacement of the starch source with forage without compromising diet energy density. Steers fed the low forage:grain diet consumed more ($P < 0.05$) DM than steers fed the high forage:grain diet during the 126-d feeding period (Table 2). The lipid content of the high forage:grain diet exceeded the target level of 7%, and as such is expected to have resulted in a lower DM intake (Krehbiel et al. 1995). The difference in intake between diets increased over the course of the experiment ($P < 0.05$). Dry matter intake (kg hd⁻¹ d⁻¹) was similar ($P = 0.78$) in period 1 for steers assigned the low forage:grain (8.3 \pm 0.6, mean \pm SE) and high forage:grain (9.4 \pm 0.6) treatments; however, the increase in DMI for steers assigned the low forage:grain diet was greater ($P < 0.05$) in periods 2 (13.0 \pm 0.6) and 3 (13.8 \pm 0.6) than for the steers fed the high forage:grain diet in periods 2 (9.4 \pm 0.5) and 3 (11.0 \pm 0.6).

Steers fed the low forage:grain diet gained more ($P < 0.05$) than steers fed the high forage:grain diet as a result of the higher DMI; thus, the feed:gain ratio was not different between the dietary treatments. The effect of diet on DMI and gain observed in the initial 126 d of feeding continued until animals went to slaughter. Steers on the high forage:grain diet took 14 d longer to reach finish condition and had significantly ($P < 0.05$) lower final body weight and body fat than steers on the low forage:grain diet at the end of the feedlot phase (Table 2). A marbling grade of A or better was achieved for 99% of steers however, the proportion of AA carcasses and rib-eye area were greater ($P < 0.05$) for the low vs. the high forage diet (75 vs. 33% and 85.9 \pm 0.9 vs. 79.7 \pm 0.9 cm, respectively).

Animal Methane Production

This study is one of the first reports of enteric CH₄ emissions from feedlot cattle under management conditions typical of Western Canada. Enteric CH₄ production was low during the course of the study, averaging less than 2% of gross energy intake (GEI) in the first two periods, increasing to 3% in the last period. Similar results (1.9 to 2.2% GEI) were observed, in a feedlot study of heifers on high grain diet, in which enteric CH₄ emissions was measured using micrometeorological mass difference technique in Australia (Harper et al. 1999). High diet digestibility (Table 1), inclusion of monensin in the diets and cold temperatures may have contributed to the low fractional losses of CH₄. The potential benefit of ionophore use has been speculated for some time (McAllister et al. 1996); however, there are

Table 2. Effects of diet on feedlot steer performance parameters (LSMeans ± SE)

Trait	Diet		Diet × Period (<i>P</i> value)
	Low forage:grain	High forage:grain	
Initial			
No. of animals	56	56	
Body weight (kg)	300.1 ± 4.23	302.4 ± 4.23	–
Body fat (mm)	1.0 ± 0.11	1.2 ± 0.11	–
Day 126			
No. of animals	56	55	
Body weight (kg)	535.1 ± 6.45 <i>a</i>	500.3 ± 6.50 <i>b</i>	–
Body fat (mm)	7.3 ± 0.23 <i>a</i>	6.0 ± 0.23 <i>b</i>	–
Day 0–day 126 ADG (kg hd ⁻¹ d ⁻¹)	1.9 ± 0.02 <i>a</i>	1.6 ± 0.02 <i>b</i>	0.23
Day 0–day 126 DMI (kg hd ⁻¹ d ⁻¹)	9.8 ± 0.04 <i>a</i>	8.4 ± 0.04 <i>b</i>	0.01
Day 0–day 126 feed:gain ratio	5.4 ± 0.07	5.4 ± 0.07	0.11
Final			
Days to market	150.8 ± 2.45 <i>b</i>	164.4 ± 2.47 <i>a</i>	–
Body weight (kg)	569.9 ± 4.88 <i>a</i>	548.5 ± 4.93 <i>b</i>	–
Body fat (mm)	7.6 ± 0.20 <i>a</i>	6.5 ± 0.21 <i>b</i>	–
Overall ADG (kg hd ⁻¹ d ⁻¹)	1.8 ± 0.03 <i>a</i>	1.5 ± 0.03 <i>b</i>	–
Overall DMI (kg hd ⁻¹ d ⁻¹)	9.8 ± 0.07 <i>a</i>	8.4 ± 0.07 <i>b</i>	–
Overall feed:gain ratio	5.5 ± 0.08	5.6 ± 0.08	–
Carcass grade (No.)			
AAA	2	–	
AA	42	18	
A	12	36	
B1	–	1	
Hot carcass wt. (kg)	315.2 ± 2.81 <i>a</i>	295.6 ± 2.83 <i>b</i>	
Hot carcass (% shrunk wt.)	57.1 ± 0.19 <i>a</i>	55.6 ± 0.19 <i>b</i>	

a–b Means within a factor in a column with different letters differ ($P < 0.05$).

Table 3. Effects of diet and sampling period on enteric methane production by steers during 126 d of feeding (LSMeans ± SE)

	DMI (kg d ⁻¹)	CH ₄ (L d ⁻¹)	CH ₄ (L kg ⁻¹ BW)	CH ₄ (L kg ⁻¹ ADG)	CH ₄ (L kg ⁻¹ DMI)	CH ₄ (% GEI)
Diet (D)						
Low forage:grain	11.7 ± 0.4 <i>a</i>	127.9 ± 6.3 <i>a</i>	0.28 ± 0.01 <i>a</i>	66.9 ± 3.5 <i>a</i>	11.2 ± 0.6	2.5 ± 0.1 <i>a</i>
High forage:grain	10.0 ± 0.4 <i>b</i>	90.0 ± 6.0 <i>b</i>	0.21 ± 0.01 <i>b</i>	56.8 ± 3.4 <i>b</i>	9.5 ± 0.6	2.0 ± 0.1 <i>b</i>
Period (P)						
1	8.8 ± 0.4 <i>c</i>	74.2 ± 6.7 <i>b</i>	0.22 ± 0.01 <i>b</i>	41.1 ± 4.0 <i>b</i>	9.4 ± 0.6 <i>b</i>	2.0 ± 0.1 <i>b</i>
2	11.2 ± 0.4 <i>b</i>	84.9 ± 6.3 <i>b</i>	0.19 ± 0.01 <i>b</i>	52.9 ± 3.8 <i>b</i>	8.0 ± 0.6 <i>b</i>	1.7 ± 0.1 <i>b</i>
3	12.4 ± 0.4 <i>a</i>	167.4 ± 6.3 <i>a</i>	0.33 ± 0.01 <i>a</i>	91.4 ± 3.6 <i>a</i>	13.7 ± 0.6 <i>a</i>	3.0 ± 0.1 <i>a</i>
D × P (<i>P</i> value)	0.01	0.01	0.01	0.02	0.03	0.02

a–c Means within a factor in a column with different letters differ ($P < 0.05$).
 $n = 20$ for diet and $n = 40$ for sampling period.

few data under production conditions to establish long term benefits. Ambient temperatures for the periods 1, 2, and 3 averaged 0.4 ± 1.1 , -8.0 ± 1.0 , and $-6.4 \pm 1.4^\circ\text{C}$ (mean ± SE). Cold exposure generally results in lowered digestibility of feed in the rumen, because of faster passage rate through the gut (Kennedy and Milligan 1978), potentially decreasing CH₄ production.

Significant diet by period interactions were observed for CH₄ production ($P < 0.05$; Table 3). The diet by period interaction showed that enteric CH₄ (% GEI) emissions were similar ($P > 0.05$) for the experimental diets at the start of the trial. Cattle fed the low forage:grain diet lost 2.19 ± 0.2 and 1.79 ± 0.2 (mean ± SE) in periods 1 and 2, respectively, while cattle fed the high forage:grain diet lost 1.86 ± 0.2 and 1.67 ± 0.2 in periods 1 and 2, respectively. As the trial progressed, enteric CH₄ (% GEI) emissions increased more rapidly for the

low forage:grain diet (3.49 ± 0.2) than for the high forage:grain diet (2.48 ± 0.2) in period 3 ($P < 0.05$). The higher body weights and intakes of animals fed the low forage:grain diet may have contributed to the more rapid increase in enteric losses for these animals. Efficiencies of fermentation changed in a similar direction over time for animals receiving the high forage and sunflower seed diet, but the degree of change was suppressed by 29% ($P < 0.05$). A similar trend of the diet by period interaction above was also apparent when CH₄ losses were calculated as L kg⁻¹ DMI or L kg⁻¹ body weight (BW). Methane production (% GEI) was 20% higher from steers on the low forage:grain diet than from steers on the high forage:grain diet ($P < 0.05$; Table 3). Overall, CH₄ production (% GEI) ranged from 0.9 to 6.9% on the low forage:grain diet and from 0.7 to 4.9% on the high forage:grain diet.

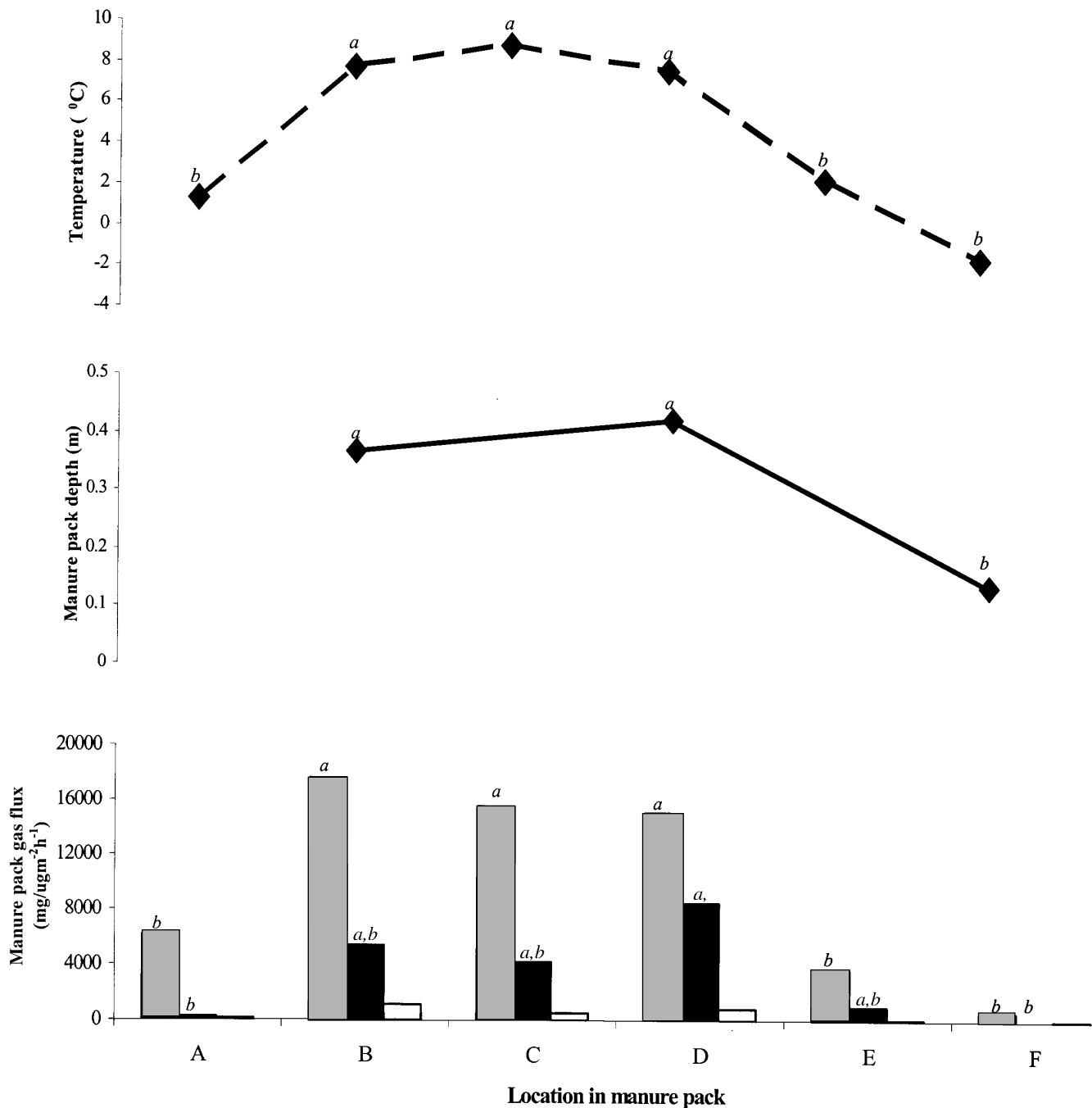


Fig. 1. Temperature, depth and GHG fluxes of manure bedding packs at various locations in period 3. Locations were measured diagonally in a straight line across the manure pack. ■, CO₂ (mg m⁻² h⁻¹), SE = 2791.8; ■, CH₄ (µg m⁻² h⁻¹), SE = 2023.4; □, N₂O (µg m⁻² h⁻¹), SE = 85.0; manure pack depth SE = 0.024 m; temperature of manure pack SE = 0.93°C. *a-c* Means within a series with different letters differ ($P < 0.05$).

The anticipated response of lower fractional CH₄ loss resulting from increased DMI and increased BW gain for the low forage:grain diet was absent in this study, when CH₄ was expressed as L kg⁻¹ DMI or L kg⁻¹ BW. This is contrary to what can be expected with higher quality diets (Harper et al. 1999; McCaughey et al. 1999; Boadi and Wittenberg 2002).

The observed lower CH₄ production from high forage:grain diet can be attributed to the effect of the high content of fat (8.3% DM basis) in the diet, which could potential reduce fiber degradation, and amount of feed that is fermentable (Mathison 1997). The addition of dietary fats to increase the energy density of high-forage diets has been shown to depress CH₄ pro-

Table 4. Effects of diet and period on greenhouse gas fluxes from manure bedding packs (LSMeans ± SE)

	CO ₂ (g pen ⁻¹ d ⁻¹ × 10 ³)	CH ₄ (g pen ⁻¹ d ⁻¹)	N ₂ O (g pen ⁻¹ d ⁻¹)	Manure pack depth (m)
Diet (D)				
Low forage:grain	34.9 ± 0.80	11.0 ± 1.90	2.2 ± 0.18	0.24 ± 0.004 _b
High forage:grain	35.7 ± 0.80	17.7 ± 1.90	2.1 ± 0.18	0.28 ± 0.004 _a
Period (P)				
1	16.7 ± 0.98 _c	16.7 ± 2.32	1.9 ± 0.23	0.21 ± 0.005 _b
2	39.0 ± 0.98 _b	10.0 ± 2.32	2.0 ± 0.23	0.27 ± 0.005 _a
3	50.1 ± 0.98 _a	16.3 ± 2.32	2.7 ± 0.23	0.31 ± 0.005 _a
D × (P value)	0.98	0.79	0.95	0.88

a–b Means within a factor in a column with different letters differ ($P < 0.05$).

duction in short-term in vitro studies (Dong et al. 1997; Machmuller and Kreuzer 1999). As well, Mathison (1997) reported that CH₄ production was reduced by 33% when 4% canola oil was added to a diet containing 85% concentrate in a feedlot study. Depressed ruminal CH₄ production with addition of dietary fats is attributed to increased levels of unsaturated fatty acids which can serve as electron acceptors during biohydrogenation (Hegarty 1999). Furthermore, long-chain fatty acids are largely non-fermentable and, therefore, decrease the percentage of CH₄ generated from the diet (Johnson and Johnson 1995). The current study demonstrates that replacement of 50% of the cereal grain in a typical feedlot ration with forage and oilseed will produce lower enteric methane emissions per unit gain compared to traditional high concentrate diets.

Manure Pack Depth and Temperature

Total straw bedding delivered to pens averaged 6342 kg pen⁻¹ for the 126 d study, with no variation among pens. As expected, average manure pack area increased during the course of the study ($P < 0.05$) averaging 212.0 ± 12.7 m². Although DMI was lower for steers assigned to the high forage:grain diet, manure pack depth was greater ($P < 0.05$, Table 4). This may be expected as digestibility, determined by IVOMD (Table 1), was lower for the high forage diet and, therefore, more structural carbohydrates are expected to have been excreted. A second explanation may be that depth was reduced as steers fed the low forage:grain diet consumed straw bedding. Consumption of bedding materials was not observed, however, since no efforts were made to monitor this behavior.

Manure pack temperature averaged 4.3 ± 0.5°C and did not differ between diets ($P > 0.05$). However, deeper sampling locations of the manure pack were significantly ($P < 0.05$) warmer than shallower sites closer to the edge of the pack (Fig. 1). It is suggested that the higher temperatures associated with deeper areas of the manure pack area reflect increased moisture and nutrient levels due to higher deposition of urine and feces (Janzen et al. 1999) and increased oxygen incorporation due to hoof action of animals, as there was a preferential use of this part of the manure pack.

Manure Pack Greenhouse Gases

Diets fed during the feedlot operation had no effect ($P > 0.05$) on the manure pack GHG fluxes (Table 4). There were no dif-

Table 5. Chemical composition of bedding manure packs (DM basis, Means ± SE)

	Low forage:grain diet	High forage:grain diet
DM (%)	29.19 ± 0.97	29.14 ± 1.15
EE (%)	0.34 ± 0.02	0.39 ± 0.03
C (%)	37.58 ± 0.94	38.81 ± 0.67
N (%)	1.39 ± 0.04	1.43 ± 0.03

ferences ($P > 0.05$) due to diet in DM, N, or C content of manure packs (Table 5). Since diets were formulated to have similar N and energy content, this can be expected. In general, the diet fed dictates the carbon:nitrogen ratio of urine and feces, which may also influence the extent of CH₄ released from manure. Jarvis et al. (1995) observed a greater rate of CH₄ release from manure with a higher N content of the diet. In their study, differences in CH₄ emission rates were observed between grain- and hay-fed animals; over 7.5 times more CH₄ kg⁻¹ dung (DM basis) was emitted from grain-fed compared to their hay-fed counterparts. Lodman et al. (1993) also observed that manure from cattle fed a high-grain diet under laboratory conditions resulted in higher CH₄ production ($P < 0.05$) compared to manure from cattle fed a forage diet. This increase was attributed to an increase in readily fermentable carbohydrates in feces from high-grain-fed animals. However, no significant differences between manure types were observed under field conditions (Lodman et al. 1993). Dilution of fecal and urinary excretions with straw bedding may mask the effect of diet. In the current study, the similar CH₄ flux observed in manure packs produced by animals fed the two diets could reflect the similarity in chemical composition of the manure. Under field conditions, variation in temperature, moisture, and time of exposure of the manure to air can be expected to produce large differences in CH₄ production from the feces of cattle managed in the feedlot (Lodman et al. 1993; Gonzalez-Avalos and Ruiz-Suarez 2001). Further studies may be necessary to account for the large variation that may exist within the manure packs as a result of trampling and defecation by animals.

Greater CO₂ and CH₄ fluxes ($P < 0.05$, Fig. 1) were observed for chambers located on the deepest parts of the manure pack. The thickest portions of the manure packs have the most favorable conditions (especially temperature) for microbial decomposition of organic matter into CH₄ and further breakdown into CO₂ (Husted 1994). Although there

Table 6. Total daily feedlot greenhouse gas emissions calculated from enteric and manure pack non-CO₂ sources (g CO₂ equivalent d⁻¹)^z per animal (LSMeans ± SE)

	Manure pack		Enteric emissions CH ₄	Total emissions per kg ADG	Total emissions
	CH ₄	N ₂ O			
Diet (D)					
Low forage:grain	16.5 ± 9.4	50.5 ± 26.6	1864.2 ± 90.3a	1931.2 ± 81.4a	1007.3 ± 41.9
High forage:grain	26.5 ± 9.4	46.0 ± 26.6	1321.8 ± 90.3b	1394.3 ± 81.4b	876.8 ± 41.9
Period (P)					
1	25.0 ± 7.2	42.3 ± 21.8	1073.4 ± 87.3b	1140.7 ± 79.0b	621.5 ± 45.2c
2	15.1 ± 7.2	43.5 ± 21.8	1241.2 ± 87.3b	1299.8 ± 79.0b	822.1 ± 45.2b
3	24.4 ± 7.2	58.9 ± 21.8	2464.4 ± 87.3a	2547.8 ± 79.0a	1382.7 ± 45.2a
D × P (P value)	0.34	0.87	0.01	0.01	0.02

^zAll emissions are expressed as g CO₂ equivalent, based on 1996 International Panel on Climate Change Guidelines.

was no effect of sampling period on CH₄ and N₂O fluxes ($P > 0.05$) CO₂ emissions significantly increased in the second and third period ($P < 0.05$).

A concern when evaluating animal feeding and management strategies to determine greenhouse gas mitigation potential is that significant emission reduction in one part of the production system may be negated if emissions are increased in another part of the production system. Table 6 demonstrates that inclusion of whole sunflower seed in general resulted in significantly lower ($P < 0.05$) total daily emissions of CH₄ and NO₂ expressed as CO₂ equivalents. The observed reduction in total emissions is attributed to a significant reduction in enteric CH₄, which contributed 95 to 96% of the total non-CO₂ emissions from the feedlot. Enteric emissions by feedlot cattle fed a typical barley-based finishing ration were 72% of that estimated by IPCC (Tier 1). Use of whole sunflower seeds in the high forage:grain diet resulted in even lower emissions relative to estimates. Similarly, manure pack emissions in the current study were approximately 50% of that estimated using IPCC (Tier 1) coefficients.

CONCLUSIONS

It can be concluded that animals fed a low forage:grain diet produce more rumen methane than animals fed a high forage:grain diet supplemented with sunflower seeds. Diet had no effect on manure pack fluxes in the presence of generous amounts of straw bedding in this study. The deeper the manure pack, the higher the manure pack temperature and, subsequently, the higher the CH₄ and CO₂ fluxes occurring in the manure packs. The resulting manure packs in feedlot pens did not show any differences in greenhouse gas emissions due to diet. Enteric emissions contributed 95–96% of the total non-CO₂ emissions from the feedlot.

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