Methane and ammonia emissions from a beef feedlot in western Canada for a twelve-day period in the fall

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[1]Agriculture and Agri-Food Canada, Research Branch, Ottawa, Ontario, Canada K1A 0C6; [2]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada T6G 2E3; and [3]Alberta Research Council, Vegreville, Alberta, Canada T9C 1T4. *Received 10 June 2008, accepted 12 June 2008.*

van Haarlem, R. P., Desjardins, R. L., Gao, Z., Flesch, T. K. and Li, X. 2008. **Methane and ammonia emissions from a beef feedlot in western Canada for a twelve-day period in the fall**. Can. J. Anim. Sci. **88**: 641–649. Commercial feedlot operations are becoming a mainstay in the Canadian beef industry. These large operations that typically raise thousands of animals at a time represent a large localized source of methane (CH_4) and of atmospheric pollutants such as ammonia (NH_3) and particulate matter. An inverse dispersion model was utilized to calculate CH_4 and NH_3 emissions from a commercial cattle feedlot and an adjacent runoff retention pond. The feedlot measurements were collected within the interior of the feedlot enabling a near continuous emissions record over the 12 d of the study period. Average daily emission estimates of CH_4 and NH_3 were 323 and 318 g animal^{-1} d^{-1}, respectively. The CH_4 emissions represent 4% of the gross energy intake (GEI) and NH_3 emissions represent 72% of the total N intake. Emissions from the runoff retention pond associated directly with the feedlot operation were approximately 2.7 and 2% of the daily average feedlot emissions of CH_4 and NH_3, respectively.

Key words: Methane, ammonia, inverse dispersion, ruminant livestock, trace gas emissions

van Haarlem, R. P., Desjardins, R. L., Gao, Z., Flesch, T. K. et Li, X. 2008. **Dégagements de méthane et d'ammoniac par un parc à bovins de l'Ouest canadien pendant douze jours à l'automne**. Can. J. Anim. Sci. **88**: 641–649. L'élevage en parc d'engraissement est sur le point de devenir la norme chez les producteurs canadiens de bovins. Les grandes exploitations qui élèvent des milliers d'animaux sont actuellement considérées comme d'importantes sources ponctuelles de méthane (CH_4) et de polluants atmosphériques tels l'ammoniac (NH_3) et les particules. Les auteurs ont utilisé un modèle de dispersion inversé pour calculer les émissions de CH_4 et de NH_3 d'un élevage commercial de bovins et de la lagune voisine où s'accumulaient le ruissellement. Les données sur le parc d'engraissement ont été recueillies à l'intérieur de l'établissement, ce qui a permis d'enregistrer presque continuellement les émissions pendant les 12 journées de l'étude. On estime les émissions quotidiennes moyennes de CH_4 et de NH_3 à respectivement 323 et 318 g par animal et par jour. Les dégagements de CH_4 représentent 4 % de la prise d'énergie brute et ceux de NH_3, 72 % du N total absorbé. Les émissions de la lagune résultant directement de l'exploitation du parc d'engraissement correspondent respectivement à environ 2,7 % et 2 % des émissions quotidiennes moyennes de CH_4 et de NH_3.

Mots clés: Méthane, ammoniac, dispersion inverse, ruminant, émissions de gaz à l'état de traces

Commercial feedlot operations are becoming quite common in the beef industry. These operations typically consist of thousands of animals and represent a significant localized source of trace gases such as methane (CH_4) and ammonia (NH_3) into the atmosphere. The quantification of these gases is essential in order to identify management practices that lead to a reduction in emissions.

In Canada, greenhouse gas emissions from agricultural sources accounted for 57 teragrams CO_2 equivalent (Tg CO_{2e}) in 2005 (Environment Canada 2007). Of these emissions approximately 15% were from manure storage systems and 44% were directly attributable to CH_4 emissions from enteric fermentation in ruminants, primarily cattle. One of the main parameters associated with enteric fermentation is the CH_4 conversion factor (Y_M), which is a function of the gross energy intake (GEI). This factor can range between 2–12% (Johnson et al. 2000). The recommended IPCC (2006) Tier 2 Y_M value for cattle whose grain diet exceeds 90% is 3%, and 6.5% for cattle whose diets have a lower proportion of grain (IPCC 2006). Canadian studies of beef cattle report Y_M estimates of between 4% for feedlot cattle and 6% for animals on pasture (Beauchemin and McGinn 2006; Ominski et al. 2006).

Factors with respect to the diet that play a role in CH_4 emissions via enteric fermentation include ration composition (Boadi et al. 2004; Beauchemin and McGinn 2006), feed quality (Harper et al. 1999) and feed

Abbreviations: **CP**, crude protein; **GEI**, gross energy intake; **MOST**, Monin-Obukhov similarity theory

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additives (McGinn et al. 2004; Guan et al. 2006). Animals raised in feedlots, as opposed to pasture, emit less CH_4 per kilogram of weight gain due to decreased forage consumption, increased grain in the diet and decreased activity (Ominski et al. 2006).

Another gas associated with feedlots is NH_3. In Canada, livestock production contributes 62% of total NH_3 emissions annually (Environment Canada 2008). Ammonia is a precursor of fine particulate matter, resulting in poor air quality, smog, and increases the susceptibility of cattle to respiratory illnesses. Respiratory diseases represent 67–82% and 50% of total feedlot morbidity and mortality, respectively (Smith 1998). Respiratory diseases account for over 80% of the total health expenses with feedlots (Apley 2006).

Ammonia emissions expressed as a percentage of N loss to the total N in the animal feed, are typically high for feedlot cattle. Measured values range from 51 to 61% (Bierman et al. 1999), 63–65% (Flesch et al. 2007), 63% (McGinn et al. 2007) and 52 to 74% (Erikson et al. 1999). A reduction in crude protein (CP) is considered effective in reducing NH_3 emissions. Todd et al. (2006) measured a 28% annual decrease in NH_3 emissions from beef cattle when CP was reduced from 12.5 to 11%. Nonetheless, an optimal quantity of CP is required for animal growth and development.

Methodologies for measuring emissions of CH_4 and NH_3 include the use of chambers (Boadi and Wittenberg 2002), tracers (Kaharabata et al. 2000; Boadi and Wittenberg 2002; McGinn et al. 2006) and micrometeorological techniques (e.g., Flesch et al. 2004; McBain and Desjardins 2005). While chambers provide a simple measurement technique that is ideal for testing treatment differences there are disadvantages: as only a small area or number of animals may be studied and conditions are unlike those in a normal production setting (Denmead and Raupach 1993; Sommer et al. 2004; Flesch et al. 2007). To obtain representative emissions estimates, the sample number should typically be on the order of 30 to 100 samples for each feedlot component (Cole et al. 2007). Furthermore, the use of chamber methods causes stress to the animal, which may influence the results (Johnson et al. 2000).

Recent advances in micrometeorological techniques (McBain and Desjardins 2005; Flesch et al. 2007) have permitted accurate emissions estimates from agricultural sources via an inverse dispersion technique. This method has the advantages, which include non-interference, and the ability to incorporate the measurement footprint over larger areas. Inverse-dispersion methods have been used with success in several studies of feedlot gas emissions (Flesch et al. 2007; McGinn et al. 2007; Loh et al. 2008). Nonetheless, there are also several limitations to using inverse dispersion methods including wind conditions and the need for source homogeneity. The objectives of this study were to quantify the daily pattern of CH_4 and NH_3 emissions from cattle in a large feedlot and adjacent retention pond using an inverse dispersion method.

MATERIALS AND METHODS

Feedlot Description

The study, which monitored CH_4 and NH_3 emissions at a commercial beef operation located in central Alberta (53°41′56″N, 111°59′09″W) was conducted over a 12-d period, 2007 Oct. 12 to 23. The "feedlot", which refers to the animal pens and associated access alleyways has a one-time capacity of 32 000 cattle. However, during the study period the average cattle population was 16 995. The feedlot is arranged into 147 pens aligned in north–south rows (Fig. 1). Each row was sub-divided into 7–10 feed pens in which the animal population ranged between 40 and 250 cattle (17–57 m^2 $animal^{-1}$) in addition to several empty pens. The average cattle population and density for each feed block during the measurement period is given in Table 1.

Three breeds of beef cattle present were: Red Angus cross, Charolais and Simmental. The average weight of the cattle during the study was 545 kg and entry and exit weights were approximately 185 and 635 kg, respectively. Overall, the cattle consumed a high grain diet consisting an average of 60% rolled barley and 10% distillers grain on a dry matter basis. The remaining portion of the feed mixture was corn and barley silage. Several feed ration mixtures were given to different feedlot pens depending primarily upon the age and size of the cattle (Tables 2 and 3). Additionally an ionophore (monensin) and several antibiotic supplements were given in the feed ration.

A portion of the cattle at the feedlot (approximately 2500) were classified as natural beef and solely received a vitamin E supplement in the feed ration. These cattle were housed in pens 1 to 27 (Fig. 1). Based on the predominant wind direction and the distance between these pens and the laser measurement location, it is anticipated that these cattle did not influence the emission estimates. Thus, all trace gas emission estimates presented within the context of this paper are based on typical feedlot management practices.

Retention Pond Description

Two retention ponds were situated at the southern end of the feedlot (Fig. 1). The ponds were relatively the same size in surface area ($\sim$2 ha). These ponds captured direct runoff from the feedlot during precipitation events. Each pond captured approximately half of the storm runoff from the feedlot area with the average volume of 91 000 m^3 during the measurement period. Inputs occurred as natural drainage down-slope to a spillway and directed under an access road, via two underground steel culverts to the ponds. Both ponds are used for irrigation of croplands surrounding the feedlot. In addition, water from the east pond is removed for use in a biodigester operation associated with the feedlot.

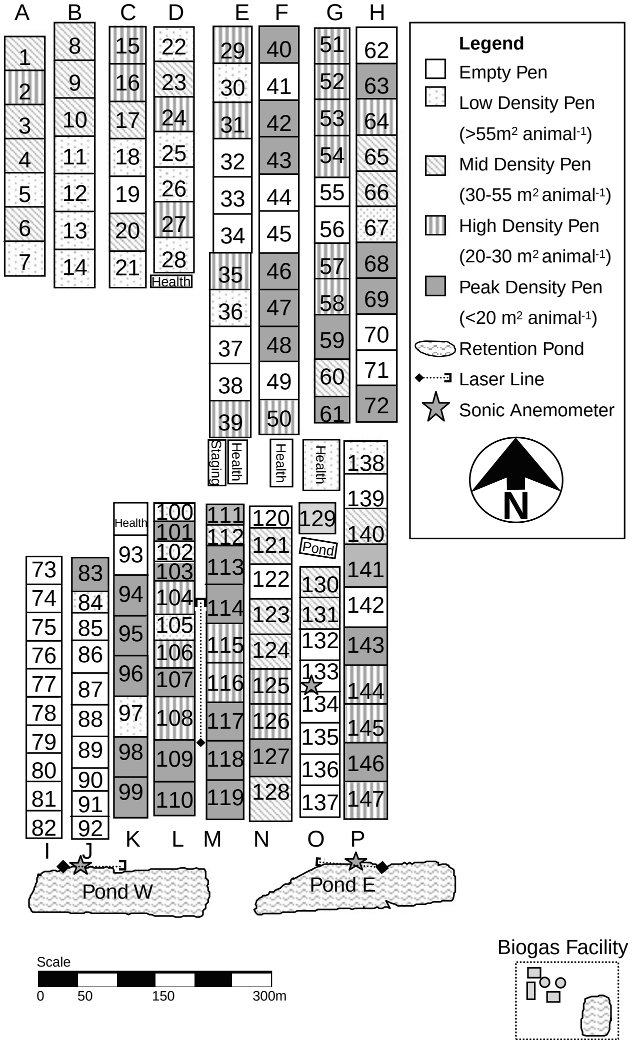

Fig. 1. Overview of feedlot and retention pond measurement arrangements during the measurement periods. The lasers and sonic anemometer configuration were located centrally in the southern portion of the feedlot and along the northern edge of each retention pond.

After the water is used in the biodigester, the liquid portion of the effluent is returned to the west pond. It is anticipated that the use in the biodigester may significantly alter the biochemistry of the pond, thus contributing to differing CH_4 and NH_3 emission rates. Thus, the west pond is not included in this analysis because the secondary use of the water for the biodigester operation may alter its chemistry to the extent that it is unrepresentative of a typical feedlot operation. Rather, the emissions from this pond will be discussed in a following paper on methane and ammonia emissions from an anaerobic digestion facility. The east pond measurements were isolated from surrounding emission sources by using a short laser pathlength, 92 m (Fig. 1) and very low measurement heights of both the open-path lasers and the sonic anemometer to ensure that the measurement fetch only included the retention pond. Additionally, this set-up allowed for measurements only during periods when the wind directions were from the south and southwest, which ensured that the emissions estimates were not affected by other potentially larger emissions sources such as the feedlot.

Table 1. Average cattle population and density for each feedblock over the duration of the study period, 2007 Oct. 12–23

Block ID	Average animal population	Average pen density (m^2 animal^{-1})
A	691	40.6
B	578	57.3
C	602	41.1
D	678	44.9
E	991	23.2
F	1500	16.6
G	1959	20.0
H	2059	21.6
I	–	–
J	256	32.6
K	1251	26.2
L	1610	38.2
M	1810	23.8
N	1581	27.7
O	449	38.9
P	1394	21.0

Measurement Strategy

Feedlot Measurements

Line average concentration (C_L) measurements of CH_4 and NH_3 were collected within the interior of the feedlot using two portable open-path laser systems (GasFinder2.0, Boreal Laser Inc, Spruce Grove, AB) over a 12-d period (Fig. 1). This arrangement was selected to ensure that emission rates could be calculated for all wind directions (i.e., no matter the wind direction, the lasers measured a concentration increase due to feedlot emissions). Both lasers were situated 1.65 m (Z_L) above the feedlot alley surface and C_L was based on an overall path length of 252 m. The C_L data were processed to provide 15-min average concentration measurements. High frequency (10 Hz) wind velocities and temperature were sampled via, a 3-D sonic anemometer (CSAT3, Campbell Scientific Inc, Logan, UT) installed approximately 180 m due east of the laser sensors at a height of 9 m above the feedlot surface to capture the boundary layer conditions of the feedlot. The sonic anemometer was situated at this level above the feedlot in order to represent the boundary layer conditions over the entire feedlot. The wind conditions at Z_L were calculated using a logarithmic wind profile as defined by the Monin-Obukhov similarity theory (MOST). These data are utilized to compute the feedlot wind environment for 15-min average periods using MOST relationships defined by friction velocity (u_*), Obukhov stability length (L), roughness length (z_0), and wind direction (β). Standard

Table 2. Feed characteristics

Ration type	Ration name	Ration composition: Rolled barley (% DM)	Silage[z] (% DM)	Distillers' grain (% DM)	Avg. dietary N (g)	GEI (MJ d^{-1})	Feed additives
Calf	AB2	20	60	10	0.147 ± 0.045	418.5	–
Yearling	CR3	30	60	10	0.198 ± 0.063	319.8	Monensin, Melengestrol acetate, Chlortetracycline, Tylosin
Yearling	CR5	50	40	10	0.337 ± 0.017	424.3	Monensin, Melengestrol acetate, Chlortetracycline, Tylosin
Yearling	CR6	60	30	10	0.360 ± 0.012	472.3	Monensin, Melengestrol acetate, Chlortetracycline, Tylosin
Yearling	CR7	70	20	10	0.383 ± 0.028	451.0	Monensin, Melengestrol acetate, Chlortetracycline, Tylosin
Organic	N7	70	20	10	0.353 ± 0.029	404.9	Vitamin E
Export	S7	70	20	10	0.385 ± 0.044	447.4	Monensin

[z] Silage consisted of 50/50 blend of barley and corn until 2007 Oct. 16 and 100% corn thereafter.

deviations of the velocity components ($\sigma_{u,v,w}$) were computed from the sonic anemometer data and used in the inverse dispersion model calculations.

An inverse dispersion model was used to compute the emission rate $(C_L/Q)_{sim}$ for each of the 15-min sampling periods. The commercially available software package WindTrax (Thunder Beach Scientific, Nanaimo, BC) utilizes a backward Lagrangian Stochastic (bLS) model (Flesch et al. 2004) to predict emissions given wind and concentration observations (i.e., emissions over 15-min intervals are calculated using the 15-min average C_L and the corresponding wind statistics). With a bLS prediction of the ratio of the tracer concentration at laser location (above the background concentration) to the emission rate, $(C_L/Q)_{sim}$, we calculate the emission rate as

$$Q = \frac{(C_L - C_b)}{(C_L/Q)_{sim}}, \tag{1}$$

where C_b is the background concentration. These $(C_L/Q)_{sim}$ are calculated using thousands of particle trajectories, which are projected upwind of the concentration sensors. The intersection between the particle and the ground is referred to as the "touchdown" and is based on the wind environment. The ensemble of these touchdowns, which is representative of the emissions footprint is given as

$$\left(\frac{C_L}{Q}\right)_{sim} = \frac{1}{N}\sum\left|\frac{2}{w_0}\right|, \tag{2}$$

where, N is the number of trajectories and w_0 is the vertical velocity at touchdown (the units of Q is in kg m^{-2} h^{-1}). The summation refers to touchdowns within the emission source, where the feedlot source areas are mapped in the software. Ten thousand touchdown particles were chosen for the emissions simulation as this was the minimum quantity needed to fulfill the minimum stochastic uncertainty in the emissions estimate of 10%. The average uncertainty for all of the measurement periods presented is then 9.5%. The quantity of touchdown particles chosen is relative to the level of uncertainty of the 15-minute average concentrations and turbulence parameters. Thus, an increase in the quantity of particle numbers would only marginally improve the emissions estimates. Threshold requirements for the 15-min average micrometeorological parameters suggested by (Flesch et al. 2004) were used in order to satisfy the assumptions in WindTrax. Thus, data that did not fulfill the following requirements were rejected:

1. periods where $u_* < 0.15$ m s^{-1} (low wind conditions),
2. where $|L| < 10$ m (strongly stable or unstable atmosphere),

Table 3. Feeding distribution of different cattle classes over the duration of the measurement period

Ration type	Ration name	No. of cattle	Avg. weight (kg)	Avg. daily intake (kg)	Avg. daily wt gain (kg)
Calf	AB2	1863	405.45	11.85	1.15
Yearling	CR3	546	391.36	9.10	1.40
Yearling	CR5	170	422.73	11.55	2.65
Yearling	CR6	191	431.82	13.25	2.73
Yearling	CR7	7414	548.18	12.60	1.65
Organic	N7	2386	604.55	11.31	1.53
Export	S7	2465	623.18	12.14	1.60

3. where $z_0 > 1$ m (associated with errors in wind profile),
4. where the fraction of the feedlot represented by the emissions estimate was $< 15\%$.

The configuration in WindTrax for calculating emissions estimates from the feedlot did not include any areas that were not occupied by cattle such as the feedlot alleys and empty pens. Furthermore, it was assumed that all occupied pens and areas within each pen possessed the same emission rates based on the relatively low deviation in animal density within the immediate measurement area (Fig. 1). Given the sampling set-up, an overestimation is anticipated for a short period during feeding as the majority of cattle are present at the feed bunks during feeding, and one set of feed bunks was relatively close to the laser setup. However, this bias is expected to be negligible when estimating average hourly emissions over several days for the whole feedlot.

Retention Pond Measurements

From Oct. 18 to 20, CH_4 and NH_3 emissions were measured from the east pond. The lasers and sonic anemometer were positioned on the north side of the pond, so that emissions could be estimated during periods of southerly winds. The measurement height (Z_L) of both lasers was 0.8 m, and the path lengths were both 92 m. Concentration data were collected every second and the 30-s averages were stored. The minimum fetch between the far south edge and the center of the laser path was about 100 h. The relatively large upwind fetch for both the anemometer and lasers ensure our measurements are within the pond boundary layer. We have thus created a situation similar to that studied in Wilson et al. (2001), whose numerical model results indicate accurate results for an inverse-dispersion calculation of pond emissions [this setup was also used by Flesch et al. (2007) in a study of pond emissions]. The wind velocities and temperature were measured using a Gill 3-D sonic anemometer (Gill Instruments Ltd., Lymington, UK) at a height of 0.8 m. Raw wind data were collected using EdiSol (University of Edinburgh) at sampling frequency of 10 Hz. Each measurement period was either accepted or rejected based on the same MOST wind statistics criteria outlined earlier for the feedlot measurements.

RESULTS AND DISCUSSION

Measurements used to calculate the emissions were taken from within the feedlot pens over a period of 12 d. Average micrometeorological conditions for the period indicate generally favourable conditions for calculating emissions using the bLS method. However, following the aforementioned prescribed boundary-layer conditions, 32% of the data were rejected due to $|L| \leq 10$ m, $u_* \leq 0.15$ m s^{-1}. The quantity of data rejected is greater than that reported by Flesch et al. (2007). However, the sample population still meets the requirements to obtain an emission estimate with a high confidence level (Gao et al. 2008). The periods rejected primarily occurred during the night-time, which is characteristically associated with extreme atmospheric stability and low wind speeds. An inspection of the 15-min average atmospheric conditions used to estimate the emissions of CH_4 and NH_3 confirmed this. Throughout the duration of the measurement period the wind direction was primarily from the southeast.

Feedlot Emissions

Fifteen-minute line average concentrations (C_L) of methane and ammonia were substantially above the background concentration levels (Fig. 2). The average C_L was 5.15 and 2.73 ppmv for CH_4 and NH_3, respectively. The average background concentrations (C_b) determined by measuring the concentrations upwind of the feedlot were 2.12 and 0.01 ppmv for CH_4 and NH_3, respectively. Although the background concentration may vary slightly due to local influences (i.e. retention ponds and biodigester operation) WindTrax was found to be relatively insensitive to minor changes in the background concentration. The gaps in the time-series displayed in Fig. 2 indicate periods where the laser and the retroreflector enclosure became misaligned during strong winds, heavy frost or routine maintenance.

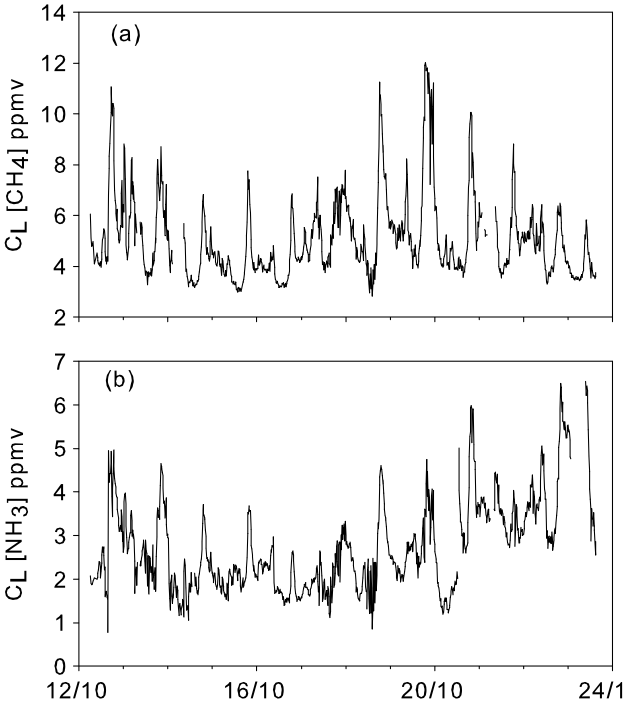

Fig. 2. A series of 15-min line average concentrations (C_L) of (a) CH_4 and (b) NH_3 collected from within the feedlot.

Methane Emissions

Feedlot emissions of CH_4 (Q_{CH4}) were calculated using the line average concentration records and 15-min average wind statistics, excluding periods which did not meet the u* and L threshold criteria. The 15-min average feedlot emission rates ranged between 0.126 and 0.773 kg CH_4 d^{-1}. The ensemble of 15-min emission values over the duration of the study period, plotted as a daily emission curve, demonstrates a strong daily pattern in CH_4 emissions (Fig. 3). The lowest emission occurred near sunrise, and the largest near sunset. Afternoon emissions were two to four times greater than the early morning rates. The variability in emission rates was greater during the daytime measurement periods than over the night-time. This daytime variability is attributed to variability in the feeding schedule and subsequent animal activity. The two feeding periods typically occurred between 0800–1000 and 1600–1800 corresponding to the two peaks in CH_4 emissions. Feeding did not occur sequentially along the feedlot rows as some pens did not receive the same feed ration as their neighbours. An hourly ensemble average 24-h emission curve, calculated from the 11 measurement days, demonstrates a relatively clear emissions pattern (Fig. 3). A strong emissions peak is noted in the morning beginning near the first feeding period and continuing as a plateau until noon (Fig. 3). This emissions plateau is clearly evident and the mean values are within the range of standard errors of the neighbouring values. An extent of the variability in the emissions rate over the morning period can be attributed to random error within the dispersion model, changes in the feedlot sampling area (i.e., measurement footprint), and measurement errors. The second maximal peak at 1800 is more pronounced as the second feeding period ends near dusk and animal activity is markedly decreased during the night-time periods.

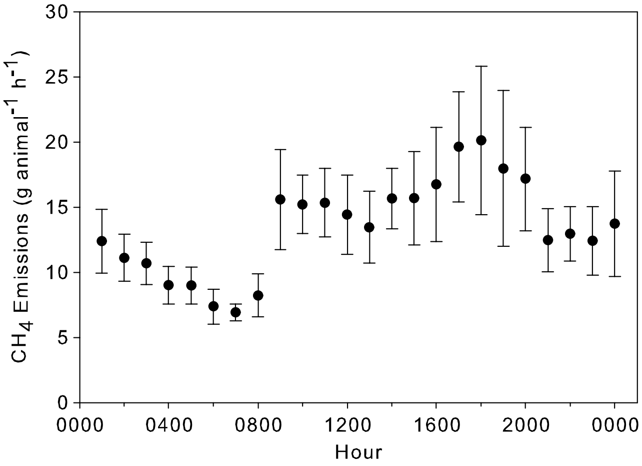

Fig. 3. Hourly average emissions and standard deviation estimates of CH_4 calculated from an ensemble average of emissions from each hourly period collected between 12 and 23 October 2007.

Our observations confirm that the pattern of CH_4 emissions closely follows the feeding pattern at the feedlot. This relationship between CH_4 emissions and feeding activity in ruminant animals is a well documented occurrence including confined dairy cattle (Kinsman et al. 1995; Jungbluth et al. 2001), grazing cattle (Harper et al. 1999; Ulyatt et al. 2002), grazing sheep (Lockyer and Champion 2001; Ulyatt et al. 2002) and cattle feedlots (Harper et al. 1999; Flesch et al. 2007).

In addition to the relationship between animal activity and CH_4 emissions, minor fluctuations in the daily emissions pattern may be due to temperature changes in the manure pack within the feedlot pens. However, it is anticipated that these changes are relatively small since manure emission estimates based on IPCC Tier 2 are approximately 0.2 g CH_4 animal^{-1} hr^{-1}. Additionally, since the measurements were conducted over a 12-d period in the fall the average daily temperature changes were relatively small ($<10°C$).

The average annual emission factor and standard deviation based on hourly weighted daily emissions over the duration of the study period were 118.1 ± 25.2 ($n=315$), kg CH_4 animal^{-1} yr^{-1}. This value does not include CH_4 emissions from manure storage, but includes emissions from manure pack within the feedlot pens.

The IPCC Tier 2 methodology suggests using a methane conversion rate (Y_M) of 3%. Using the feed ration information and the IPCC suggested Y_M, annual emission estimates for enteric fermentation and manure are 87.1 and 1.9 kg CH_4 animal^{-1} yr^{-1}, respectively. Collectively, these emissions estimates are 24.6% lower than the emissions calculated from our feedlot measurements. When IPCC Tier 2 methodologies are coupled with Canadian emission parameters for finishing beef cattle consuming a high-grain diet ($Y_M = 4\%$), the emission estimates for enteric fermentation and manure are then 116.9 and 1.9 kg CH_4 animal^{-1} yr^{-1} respectively. These emission estimates are very similar to the estimates calculated for the feedlot under study. The Y_M calculated from this study based on the measured CH_4 emissions and the weighted average GEI (434.3 MJ animal^{-1} d^{-1}) is approximately 4%.

Ammonia Emissions

A 24-h pattern also exists for the NH_3 emissions (Fig. 4); however, it not as closely related to the feeding schedule as the CH_4 emission pattern. This may in part be due to fact that the emissions of NH_3 are not a direct process as compared with CH_4 emissions produced by rumination and are more dependent upon temperature and atmospheric conditions (Sommer et al. 2004; Flesch et al. 2005a). Nonetheless an ensemble of hourly average emissions collected over the duration of the measurement period demonstrates a clear daily trend. Similar to

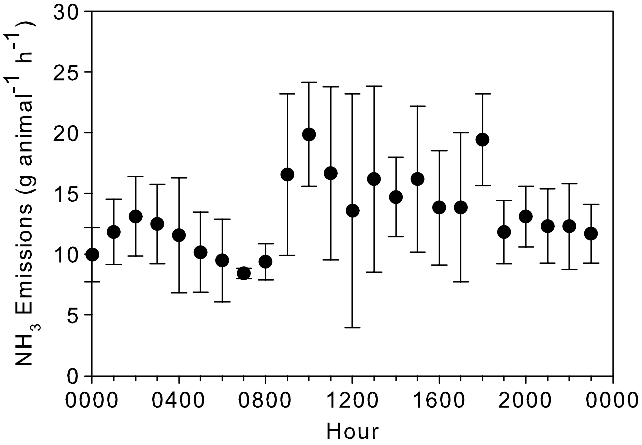

Fig. 4. Hourly average emissions and standard deviation of NH_3 estimates calculated from an ensemble average of emissions from each hourly period during the period between 12 and 23 October 2007.

the CH_4 estimates, an hourly emission estimate was calculated from an ensemble of data. The daily NH_3 emission pattern displays greater variability than CH_4 emissions within each hourly period. This change in variability is most likely due to the strong linkages exhibited between mechanical turbulence, often expressed as friction velocity, temperature and NH_3 emission rates (Flesch et al. 2005b; McGinn et al. 2007). A pronounced midday plateau in emissions is evident followed by a gradual increase in emissions until a sharp decline near dusk (Fig. 4). Average emission and standard deviation per animal over the duration of the measurement period were 0.318 ± 0.098 ($n = 315$), kg NH_3 d^{-1}. The emissions are extremely large in comparison with previous studies of NH_3 emissions from beef cattle ranging from 0.05 kg animal^{-1} d^{-1} (Hutchinson et al. 1982) to 0.15 kg animal^{-1} d^{-1} (Flesch et al. 2007).

Analysis of the feed data during the study indicates that the daily average N intake was approximately 364 ± 16 g N animal^{-1}, thus approximately 72% of the N intake was emitted as NH_3. The large magnitude of NH_3 emission rates observed when we express the corresponding N:NH_3 loss as a percentage of dietary N generally exceed the range observed in other studies: 51–61% (Bierman et al. 1999), 63–65% (Flesch et al. 2007), 63% (McGinn et al. 2007) and 52 to 74% (Erikson et al. 1999). The absolute NH_3 emissions and N intake are both elevated in comparison to these other studies, as the diet in the study feedlot is excessively higher in CP. This confirms the critical role of CP in determining NH_3 emissions. The key component of the feed ration that markedly increased the quantity of CP intake was distillers' grain, which has a CP of approximately 40% dry matter. An optimal CP for animal growth and N retention range between 11.5 and 13% (Cole et al. 2005). In addition, the authors state that as animals mature less CP is required. In order to assess the excess CP intake in the diet of the cattle during the study, the diet and feed consumption rates of the cattle are compared with the maximum suggested CP intake of 12.5% CP in the United States (National Research Council 1996). Using the same feed intake rate (12 kg animal^{-1} d^{-1}) the average daily NH_3 emissions would be reduced to 0.164 kg NH_3 animal^{-1} d^{-1} if the CP intake was 12.5%. Excess CP that is consumed is typically voided as urea in urine, which is then converted to NH_3 by microbial ureases and in turn is rapidly volatilized resulting in excess emissions of 0.127 kg N animal^{-1} d^{-1}. At this ideal lower CP intake level, the ratio of dietary N intake to N-NH_3 emissions would account for 57% of the total N intake, which is in good correspondence with previous studies.

Although a large portion of the excess NH_3 emissions can be attributed to the high dietary-N intake, other factors may cause potential biases in the emissions estimate. As previously highlighted, the animals are assumed to be evenly distributed throughout each feeding pen. As NH_3 emissions occur primarily from conversion and subsequent volatilization of urea in urine and a small continuous contribution from N mineralization in manure, a bias in the measurements may exist as the manure-pack was deeper near the feeding bunk. It is also assumed that a disproportionate quantity of urine is deposited closer to the feed bunk. Furthermore, visual observations would conclude that the areas near the feed bunks were wet, probably from increased urine deposits, compared with the back section of the pens where the soils appeared dryer. Urine was the only source of moisture as only a negligible quantity of precipitation (~2 mm) fell on the day prior to the study. When all of these sources are considered, it is possible that the NH_3 emissions may be slightly overestimated; however, the excess CP intake is the predominant factor contributing to the high NH_3 emission estimates.

Pond Emissions

Methane Emissions

The average daily emission and standard deviation from the runoff pond were 105 ± 18.7 ($n = 48$) kg CH_4 d^{-1}, which represents 3% of the CH_4 emissions from the feedlot during the measurement period. Although the emissions from the runoff pond are substantially lower in comparison to the feedlot it should be noted that these emissions may display a strong degree of seasonal variability as the present emissions were collected when daily average air temperatures were 8.5°C and heavy frost was reported on some occasions. A strong positive correlation between temperature and CH_4 emissions was recorded in nutrient retention ponds by Stadmark and Leonardson (2005) and an anaerobic swine lagoon consisting of a manure slurry by Sharpe and Harper (1999). Nonetheless, despite a predicted variability in

CH_4 emissions over an annual period these emissions are still small in comparison to those of the feedlot.

Ammonia Emissions

For the measurement period, the mean emission rate of NH_3 from the runoff pond was 17 ± 15.9, ($n = 48$) kg NH_3 d^{-1}, which accounted for about 0.4% of the total intake N by the cattle. On a per area basis, the resultant value of 8.6 kg NH_3 ha^{-1} d^{-1} is in a good agreement with the value of 8–9 kg NH_3 ha^{-1} d^{-1} reported by Flesch et al. (2007). Similar to CH_4 emissions, it is anticipated that seasonal variability in emissions will exist to some extent. Nonetheless, the emissions presented are smaller than emissions occurring during the summer and larger than those occurring during the winter, which are typically negligible after ice formation.

CONCLUSIONS

Methane and ammonia emissions from a commercial feedlot were estimated using a bLS inverse-dispersion model. Near continuous estimates were obtained as the measurement location within the feedlot permitted measurements from all wind directions. These measurements provided average emission estimates of 0.318 kg NH_3 $animal^{-1}$ d^{-1} and 0.323 kg CH_4 $animal^{-1}$ d^{-1}. The CH_4 emission corresponds to a Y_M of 4% which agrees with Canadian literature. The estimate of NH_3 emission is markedly greater than most values reported (72%). However, if the dietary N intake is taken into account, the ratio of N loss from NH_3 emissions to the total dietary N intake is 57%, a value which is in agreement with other studies. Finally, the possibility of biases in the measurements due to animal distribution in the individual pens cannot be eliminated.

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