Running head: Feed efficiency and methane emissions in beef cattle

Methane and carbon dioxide emissions from yearling beef heifers and mature cows classified for residual feed intake under drylot conditions

Manafiazar[1], G., Baron[2], V.S., McKeown[3], L., Block[2], H., Ominski[4], K., Plastow[1], G., and Basarab[1, 3] J.A.

[1]Livestock Gentec, Department of Agricultural, Food and Nutritional Science, University of Alberta, Edmonton, AB, Canada, T6G 2P5;

[2]Agriculture and Agri-Food Canada, Lacombe Research and Development Centre, 6000 C & E Trail, Lacombe, AB, Canada, T4L 1W1;

[3]Alberta Agriculture and Forestry, Lacombe Research and Development Centre, 6000 C & E Trail, Lacombe, AB, Canada, T4L 1W1;

[4]University of Manitoba, Department of Animal Science, Winnipeg, MB, Canada, R3T 2N2

Corresponding author: John Basarab, E-mail: john.basarab@gov.ab.ca

Telephone: (403) 350-9620

Postal address: Alberta Agriculture and Forestry, Lacombe Research and Development Centre, 6000 C & E Trail, Lacombe, AB, Canada, T4L 1W1

Manafiazar, G., Baron, V.S., McKeown, L., Block, H., Ominski, K., Plastow, G., and Basarab J.A. 2018. **Methane and carbon dioxide emissions from yearling beef heifers and mature cows classified for residual feed intake under drylot conditions**

This study quantified methane (CH_4) and carbon dioxide (CO_2) production from beef heifers and cows classified for residual feed intake adjusted for off-test backfat thickness (RFI_{fat}), and reared in drylot during cold winter temperatures. Individual performance, daily feed intake and RFI_{fat} were obtained for 1068 crossbred and purebred yearling heifers (eight trials) and 176 crossbred mature cows (six trials) during the winters of 2015-2017 at two locations. A portion of these heifers (147 high RFI_{fat}; 167 low RFI_{fat}) and cows (69 high RFI_{fat}; 70 low RFI_{fat}) were monitored for enteric CH_4 and CO_2 emissions using the Greenfeed Emissions Monitoring (GEM) system (c-lock Inc., Rapid City, SD, USA). Low RFI_{fat} cattle consumed less feed (heifers, 7.80 vs. 8.48 kg DM d^{-1}; cows, 11.64 vs. 13.16 kg DM d^{-1}; $P<0.001$) and emitted less daily CH_4 (2.5% for heifers; 3.7 % for cows) and CO_2 (1.4% for heifers; 3.4% for cows) compared with high RFI_{fat} cattle. However, low RFI_{fat} heifers and cows had higher CH_4 (6.2% for heifers; 9.9% for cows) and CO_2 yield (7.3% for heifers; 9.8% for cows) per kg DMI compared with their high RFI_{fat} pen mates. The GEM system performed at air temperatures between +20 and -30 ^{o}C. Feed intake of heifers and mature cows were differently affected by ambient temperature reduction between +20 and -15^{o}C, and similarly increased their feed intake at temperatures below -15 ^{o}C. In conclusion, low RFI_{fat} animals emit less daily enteric CH_4 and CO_2, due mainly to lower feed consumption at equal body weight, gain and fatness. These results further support the potential of selecting for low RFI as a strategy for reducing greenhouse gas emissions in beef cattle.

Key words: Beef cattle, methane, carbon dioxide, residual feed intake, drylot, cold temperature

Abbreviations: ADF, acid detergent fiber; **ADG**, average daily gain; **BW,** body weight; **CH_4,** methane; **CO_2,** carbon dioxide; **DMI**, dry matter intake; **GEM**, GreenFeed emission monitoring, **KIN,** Roy Berg Kinsella Research Station; **LRDC**, Lacombe Research and Development Center; **MMBW,** mid-test metabolic body weight; **NDF,** neutral detergent fiber; **RFI,** residual feed intake; **RFI_{fat}**, residual feed intake adjusted for off-test back fat thickness; **SDMI,** standardized dry matter intake; **SF_6**, sulphur hexafluoride; **RC,** respiratory chambers

Genetic selection for low residual feed intake (RFI) has been suggested as a permanent and cumulative strategy for reducing methane (CH_4) and greenhouse gas (GHG) emissions while improving profitability of beef cattle production (Alford et al. 2006). Residual feed intake is moderately heritable (0.29-0.46) and moderately repeatable (0.33-0.62) across animal types and diets (Crews et al. 2003; Kelly et al. 2010*a*; Basarab et al. 2011; Durunna et al. 2013). However, the actual GHG mitigation potential of selecting for low RFI (efficient) cattle remains uncertain (Hegarty et al. 2007; Fitzsimons et al. 2013; McDonnell et al. 2016; Alemu et al. 2017) as CH_4 emissions have rarely been measured under actual beef cattle production systems, particularly in cold environments.

Respiratory chambers (RC) and sulphur hexafluoride (SF_6) are widely used techniques to measure individual cattle CH_4 emissions (g d^{-1}). Respiratory chambers are often referred to as the "gold standard" for emission measurements, with individual animals studied for 1-3 d (Alemu et al. 2017). However, inside the chamber the animal's feed intake is reduced, feeding behaviours are altered, and short-term CH_4 measurements are unlikely to reflect longer-term CH_4 emissions in production systems (Hegarty et al. 2007; Harper et al. 2011; Alemu et al. 2017). The SF_6 tracer technique can be used under grazing conditions but requires daily handling to exchange collection chambers, as well as cleaning and maintenance of equipment between measurements (Harper et al. 2011). This limits the number of animals that can be monitored by SF_6, and it is more appropriate for dairy cattle that are more accustomed to daily handling than beef cattle (Harper et al. 2011). Alternatively, the GreenFeed Emissions Monitoring (GEM) system (c-lock Inc., Rapid City, SD, USA) is a non-invasive method used to monitor CH_4 emissions from individual animals. The GEM system requires less animal training, and emissions can be measured repeatedly in real-time over multiple 24-hr periods without the need to remove animals from their production environments (Manafiazar et al. 2017; Arthur et al. 2017). Numerous studies have used the GEM, RC and SF_6 techniques to quantify CH_4 emission under various management and nutritional strategies (Hammond et al. 2016; Manafiazar et al. 2017; Arthur et al. 2017). Hegarty et al. (2007) monitored CH_4 emissions from 76 Angus steers using the SF_6 technique and concluded that a one kg reduction in breeding value for RFI decreased daily CH_4 emission by 13.38 g d^{-1}, and low RFI heifers emitted 25% less CH_4 daily than high RFI heifers. Alemu et al. (2017) monitored 16 replacement heifers during May-June, previously classified for RFI adjusted for off-test backfat thickness (RFI_{fat}), for 25 days using GEM and RC systems, and reported lower CH_4 emissions (10% by GEM; 5% by RC) in low RFI_{fat} compared with high RFI_{fat} replacement heifers. However, CH_4 yields were similar between high and low RFI_{fat} groups, respectively, at 27.7 and 28.5 g kg DMI^{-1} for GEM and 26.5 and 26.5 g kg DMI^{-1} for RC. Fitzsimmons et al. (2013) tested 22 Simmental heifers using the SF_6 method and reported that low RFI animals emitted less CH_4 compared to high RFI animals (260 vs. 297 g d^{-1}) and had lower CH_4 production (2.5 vs. 2.9 g kg $BW^{-0.75}$). Overall, studies quantifying the mitigation potential of RFI have had low animal number or used techniques that have a significant impact on the animals' feeding behaviours. In addition, over 80% of Canadian beef cattle are located in the western provinces and exposed to cold (>-20^{o}C) winter temperatures and wind chill that affect feed intake (Webster et al. 1970; National Research Council 2016). Thus, our objective was to compare CH_4 and carbon dioxide (CO_2) emissions from beef cattle classified for RFI_{fat} and reared in drylot during cold winter conditions using the GEM system.

MATERIALS AND METHODS

Animal care committees at the University of Alberta and Lacombe Research and Development Center approved the study, and all animals were cared for in accordance with the guidelines of the Canadian Council on Animal Care (Olfer. et al. 1993).

Data Acquisition and Animals

Performance data

This study consisted of eight trials using crossbred and purebred yearling beef heifers ranging in age from 9.2-10.9 mo and six trials using crossbred beef cows ranging in age from 2.6-7.2 yr at start of trial. Trials were conducted during the winters of 2015, 2016, and 2017 at the Roy Berg Kinsella Research Station (KIN) and Lacombe Research and Development Center (LRDC), Alberta, Canada. In 13 of 14 trials a minimum of 21 d adaptation period was followed by a 72-86 d measurement period. In Trial 3 a 21-d adaptation period was followed by a 114 d feed intake measurement period due to measuring three groups of heifers through the GEM system. Heifers at LRDC were crossbreds consisting of Aberdeen Angus × Hereford and Charolais × Red-Angus, while heifers at KIN were primarily crossbreds of Aberdeen Angus, Charolais, Hereford, and Limousin and purebred Aberdeen Angus and Charolais. During each trial, animals were co-mingled in multiple drylot pens (46 m^2 per animal) fitted with 24 automated feeding stations (GrowSafe Systems Ltd., Airdrie, AB) at LRDC and 40 stations at KIN (minimum of 29.3 m^2 per animal) resulting in feeding density of 6-8 animals per GrowSafe station. Daily feed intake (kg DM d^{-1}) and feeding event behaviors (events d^{-1}; duration, min d^{-1}; head down time, min d^{-1}) were measured as previously described by Basarab et al. (2003, 2011). Replacement heifers were fed a high forage diet *ad libitum*, twice daily, while cows were fed a high forage-based diet once daily at KIN and LRDC (Table 1). Feed samples were collected weekly and stored at -20°C until they were composited by month and analyzed for dry matter (DM), calcium, phosphorus, crude protein, neutral detergent fibre (NDF) and acid detergent fibre (ADF). Dry matter was determined by drying a sample of the diet at 80 ^{o}C in a forced-air oven to a constant weight. Calcium and phosphorus contents of the samples were determined by AOAC method 985.01 with the following modifications; 0.35 g of sample was ashed for 1 hr at 535 °C, digest in open crucibles for 20 min in 15% nitric acid on hotplate, and samples were diluted to 50 ml and analyzed on ICP (AOAC 2000). Nitrogen content was determined by Kjeldahl with crude protein calculated as 6.25 × N% (AOAC 2000). Neutral detergent fibre and ADF were determined according to Van Soest method (Van Soest et al. 1991). Diet ingredients and chemical compositions for each trial are presented in Table 1. Animals had ad libitum access to water, and pens were bedded with woodchips as needed. Animals were weighed prior to morning feeding on two consecutive days at the start and end of the feed intake test period and at approximately 28-d intervals throughout. Each animal was measured for backfat thickness at the 12-13th rib (mm) using an Aloka 500V diagnostic real-time ultrasound with a 17 cm 3.5 M Hz linear array transducer (Brethour 1992) at the end of the trial.

RFI_{fat} calculation

Residual feed intake adjusted for off-test backfat thickness (RFI_{fat}) was calculated for each animal within trial using performance and feed intake data. Details of RFI_{fat} calculation have been described by Basarab et al. (2007, 2011) and Manafiazar et al. (2015). Briefly, mean daily feed intake as measured by the GrowSafe® Feed Intake system, and mean daily pellet intake as measured by the GEM system were each multiplied by their respective DM content and then summed to give total mean daily dry matter intake (DMI). Standardized DMI (SDMI) was calculated for each animal by multiplying total mean daily DMI by the metabolizable energy content of the diet, and then dividing by 10 to standardize the diet to 10 MJ ME kg DM^{-1}. Initial on-test body weight, metabolic mid-weight (MIDWT) and average daily gain (ADG) were calculated from the linear regression of each animal's observed BW against day on test (Basarab et al. 2003; Manafiazar et al. 2015) using PROC GLM (SAS 2016). The RFI_{fat} was calculated as the difference between SDMI and predicted SDMI for each animal using the following model:

$$Model\ 1: Y_{ijk} = \beta_0 + PEN + \beta_1 ADG_i + \beta_2 Metabolic\ MIDWT_j + \beta_3 UBFEND_k + e_{ijk}$$

where, Y_{ijk} is the SDMI for animal *ijk*, β_0 is the regression intercept, *Pen* is the fixed effect of pen, β_1 is the partial regression coefficient of SDMI on ADG (kg d^{-1}), β_2 is the partial regression coefficient of SDMI on metabolic mid-weight (kg), β_3 is the partial regression coefficient of SDMI on final ultrasound backfat thickness (UBFEND, mm), and e_{ijk} is the random error term. Animals were excluded from RFI_{fat} calculation if their linear growth curve had coefficients of determination (R^2) of less than 0.90.

Enteric CH_4 and CO_2 measurements

Simultaneously with the RFI tests, one GEM system was located in a pen within each location (LRDC and KIN), and different groups of animals rotated through the GEM pen to be monitored for enteric CH_4 and CO_2 emissions. Animals voluntarily visited the GEM system, which recorded beginning and end time of each visit, visit time and number of visits per day. Animals were accustomed to visit and consumed pellets from the GEM system two weeks before each test period. The GEM systems were programmed such that each animal was allowed to receive a maximum of six pellet drops from the unit every four hr and could have up to six visits per d for a maximum of 36 pellet drops per d. Average pellet drop weight was 31.1 g (SD=0.2), 30.2 g (SD=0.3) and 32.7 (SD=0.2) in 2015, 2016 and 2017, respectively, for the unit located in LRDC. Average pellet drop weight was 40.8 g (SD=0.2), 39.8 g (SD=0.1) and 39.3 g (SD=0.2) in 2015, 2016 and 2017, respectively, for the unit located in KIN. Pellets consisted of barley, corn distillers grain screenings, soy meal, wheat millrun, beef vitamin/trace, mineral pre-mix, CaCO3, chelated zinc, manganous oxide, and sodium chloride (Masterfeeds, AB, Canada). Average pellet chemical compositions were 79.7% TDN, 14.7% CP, 5.5% ADF, 14.2% NDF, 2.04% Ca, and 0.47% P.

Methane emissions were measured from the GEM system as described by Manafiazar et al. (2017). In brief, continuous and negative air flow from a system fan draws air past the animal's nose and mouth when it enters the shroud, thus mixing air with respired and/or eructated CH_4 and CO_2. This mixture is drawn up a collection pipe, remixed, sampled and analyzed by a nondispersive infrared analyzer. The unit also continuously collects samples from background CH_4 and CO_2 concentrations in a similar manner without presence of animals. The units were calibrated weekly for CH_4 and CO_2 using a zero (semi-pure nitrogen) and span gas (CO_2 = 5054 ppm for KIN unit, and CO_2 = 5144 ppm for LRDC unit, and CH_4 = 487 ppm and the balance gas of nitrogen for both units), and dilution rate was determined by releasing a small amount (~10 ml) of propane every 5 hr. The CO_2 recovery test was performed at the beginning of each trial and every month throughout. The recovery rate was 99% ± 5.5% for 3 min of CO_2 release into the GEM system. Raw data included time of visits, CH_4 and CO_2 concentration from background, sum of animal respiration and eructation, dilution factor, and calibration information were uploaded to c-lock Inc., where it was stored, processed and then downloaded through the internet for further analysis. More details on data processing from GEM and operative procedure are described by Manafiazar et al. (2017).

Climate Data

Climate condition data was acquired from Alberta Agriculture online weather data site (http://www.agric.gov.ab.ca/acis/alberta-weather-data-viewer.jsp). Climatic data for LRDC were from a weather station located one km east of the outdoor feed intake pens, while KIN climatic data was collected from a weather station located 5 km straight north of the outdoor feed intake pens. These data included year, month, day, daily precipitation (mm), air temperature (^{o}C), minimum and maximum of air temperature (^{o}C), relative humidity (%), wind speed (km h^{-1}) and wind direction (0-360^{o} with 0 being North). A wind chill index was calculated as:

Wind chill index, ^{o}C = 13.12 + 0.6215**T** - 11.37$\mathbf{V}^{0.16}$ + 0.3965**T** x $\mathbf{V}^{0.16}$, where T=ambient temperature in degrees C and V = wind speed in km hr^{-1}.

Data preparation and statistical analysis

Data preparation

Raw data generated by the GEM system and uploaded to c-lock Inc. website were stored in files named COMMAND, DATA, FEED, and RFID. The COMMAND file includes date and time of commands for calibration, heater on or off, feeder on or off, and fan on or off. The DATA file has time (MM/DD/yyyy HH:mm:ss), released pellets associated with time, and drop setting. The FEED file contains time, animal identification and received drops associated with the time, and drop setting. The RFID file contains animal identification, the time when an animal was detected and when the animal left the unit. The raw data was downloaded to a local PC, and pre-developed EXCEL worksheets from c-lock Inc. were used to compile the raw data and generate CH_4 and CO_2 emissions, visit frequency, total valid visit duration, and visit time for each visit (MM/DD/yyyy HH:mm:ss). Total valid visit duration was defined as the amount of time spent in the GEM system where the animal's head was continuously in the shroud within 20 cm of the proximity sensor for a minimum of two min. Total number of drops per day for each animal was also extracted from the c-lock Inc. webpage. Visit data were then converted to daily emission data using SAS software program (SAS 2016) by rolling average for CH_4 and CO_2 and by summing total valid visit duration and visits frequency per day for further analysis. Daily data generated by GEM were matched to daily feed intake data using animal identification and date. Enteric CH_4 and CO_2 production are expressed as emission (g d^{-1}) and yield (g kg^{-1} DMI). Descriptive statistics were attained using PROC MEANS in SAS statistical software package (SAS 2016).

A total of 1133 animals were tested for daily feed intake, but 65 animals were excluded from RFI_{fat} calculation as their linear growth curve had coefficients of determination (R^2) of less than 0.90. The number of animals in each feed efficiency test, start date and number of animals that voluntarily visited the GEM system are presented in Table 1. Heifers averaged 2.75 visits d^{-1} and cows averaged 2.40 visits d^{-1} to GEM system and were monitored on average 43 d (ranged from 20 to 63 d) within trial. A total of 28 heifers and eight cows were excluded from analysis since they had lower than 20 spot visits to the GEM system during the monitoring times (Manafiazar et al. 2017), leaving 314 heifers (147 high and 167 low RFI_{fat} heifers in eight trials) and 139 cows (69 high and 70 low RFI_{fat} cows in six trials) for further analysis (Table 2). Response variables included CH_4 and CO_2 emission (g d^{-1}), yield (g kg DMI^{-1}), and ratio (g CH_4 g CO_2^{-1}), and number of visits to GEM (visits d^{-1}), pellet intake (kg d^{-1}), DMI (kg d^{-1}), average daily gain (ADG, g d^{-1}), and ultrasound off-test back fat thickness (mm).

Statistical analysis

Enteric gas and performance traits were subjected to analysis of covariance using PROC MIXED in SAS statistical software package (SAS 2016). Mid-point weight, ADG, RFI, and off-test back fat thickness were subjected to analysis using Model I that included RFI_{fat} group, trial, and interaction of RFI_{fat} group by trial as fixed effects and animals nested in days of test and error as random effects.

Model I: $Y_{ijkl} = \mu + RFI_i + Trial_j + RFI \times Trial_{ij} + Animal\ (Day)_{kl} + e_{ijkl}$

Enteric CH_4 and CO_2 traits were subjected to analysis using Model II with fixed and random effects as described for Model 1, as well as number of visits over the test period (Nvisits) and total of valid visit duration time during the test period (Tvisits) as covariates.

Model II: $Y_{ijklmn} = \mu + RFI_i + Trial_j + RFI \times Trial_{ij} + Animal\ (Day)_{kl} + \beta_1 Nvisits_m + + \beta_2 Tvisits_n + e_{ijklmn}$

The PROC SGSCATTER was used to generate graphs for the relationships between ambient temperature and traits of interest, while PROC REG was used to quantify associations of wind chill index with DMI, CH_4 and CO_2 production.

RESULTS AND DISCUSSION

Diurnal pattern of enteric CH_4 and CO_2 emissions

Diurnal patterns of enteric CH_4 and CO_2 emissions were generated by averaging daily CH_4 and CO_2 across animals and trials by hour of day for heifers (Figure 1) and cows (Figure 2). These figures illustrate that CH_4 and CO_2 emissions began to increase rapidly for heifers and cows from 0900 to 1000 hr, which coincided with feed delivery between 0830 to 0900 hr. Peak emissions for cows occurred between 1300-1800 hr and then started to decline after 1800 hr as they were fed once in the morning. However, emissions for the heifers peaked between 1800-2000 hr due to a second feed delivery at approximately 1530-1630 hr. Maximum CH_4 and CO_2 emissions (peak point) over the pattern were divided by their minimum emissions (nadir point) to estimate maximum variability of diurnal pattern of CH_4 and CO_2 emissions over 24 hr. The variability for CH_4 emissions were 1.48 and 1.85 from replacement heifers and cows, respectively. The variability for CO_2 emissions were 1.43 and 2.1 for replacement heifers and cows, respectively. Cows had a more variable CH_4 and CO_2 diurnal pattern compared to heifers, likely due to increased variability in age (2.6-7.2 yr for cows; 9-11 mon of age for heifers), body weight (532-769 kg for cows; 226-370 kg for heifers) and feed intake of cows compared with heifers.

Diurnal pattern of CO_2 emission had lower variation compared to CH_4 in both cows and heifers. Both enteric CH_4 and CO_2 emissions and yields are proportional to DM intake (Grainger et al. 2007). In addition, CO_2 is proportional to energy expenditure, and at a given level of energy intake, CO_2 output is much less variable than enteric CH_4 (Hegarty 2013). Methane emissions were found to be most affected by feed intake, diet composition, and feeding frequency (Hegarty 2013; Knapp et al. 2014; Manafiazar et al. 2017). Crompton et al. (2010) fed lactating dairy cows at different intervals with 1, 2, or 4 times equal feeding daily. Higher variability (2.5 nadir point) was reported when animals were fed once daily, and the lowest variability (1.6) was observed when animals were fed 4 times daily (Crompton et al. 2010). This also further explains higher variability of cows in our study, which were fed once compared to heifers that were fed twice daily. Zimmerman et al. (2013) reviewed variability of CH_4 diurnal pattern using the GEM system and reported a range of 1.2 to 1.6. In all studies, lowest CH_4 and CO_2 emissions occurred just before feeding in the morning and highest emissions occurred in the afternoon after second feeding. Our results of CH_4 emission pattern are comparable with previous studies.

Performance, feeding behaviour, feed intake and CH_4 and CO_2 production

Heifer and cow performance during the feed efficiency test periods at LDRC and KIN are presented in Table 2. High and low RFI_{fat} heifers and cows were similar in on-test age, test mid-point weight, ADG, and off-test back fat thickness, but differed in RFI_{fat} by 0.78 kg DMI d^{-1} for all heifers and by 1.11 kg DMI d^{-1} for all cows tested. Among animals that visited the GEM system, high and low RFI_{fat} heifers and cows were also similar in on-test age, test mid-point weight, ADG, off-test back fat thickness, and in magnitude of difference for RFI_{fat} (0.73 kg DMI d^{-1} for heifers; 1.21 kg DMI d^{-1} for cows). These results are consistent with previous results reported by other researchers (Kelly et al. 2010*b*; Durunna et al. 2013; Basarab et al. 2007, 2011). In our study, 79 cows were also feed efficiency tested as heifers, and showed moderate positive ($P<0.001$) correlations for RFI_{fat}, (r_p= 0.36), DMI (r_p= 0.33), final back fat thickness (r_p= 0.63) and MIDWT (r_p= 0.66) of heifers and cows. These results were expected as positive and moderate to high phenotypic and genetic correlations have been reported by (Archer. et al. 2002) between heifer post-weaning and mature cow RFI (r_p= 0.40; r_g= 0.98), DMI (r_p= 0.51; r_g= 0.94), ADG (r_p= 0.28; r_g= 0.72), and MIDWT (r_p= 0.70; r_g= 0.82).

During the GEM monitoring period, low RFI_{fat} females consumed less feed (heifers 8.7%; cows 13.1%), spent less time in the feeding bunk (heifer 6.5%: cows 5.5%) and had less head down time (heifers 19.7%; cows 3.6%) with fewer visits to the bunk (heifers 18.1%; cows 6.8%) compared with high RFI_{fat} females (Table 3). These results are consistent with those of others who compared feed intake and feeding behaviour between different groups of beef yearling heifers classified for RFI_{fat} (Kelly et al. 2010*b*; Durunna et al. 2013; Kayser and Hill 2013). High RFI_{fat} heifers visited the GEM system more frequently and spent more time at each visit and received more pellets from the unit compared with low RFI_{fat} heifers, while high and low RFI_{fat} cows were similar in visit frequency and visit time to GEM. This latter result may have been due to the familiarity of 79 cows with the GEM system when they were exposed to it as heifers.

The main effect of RFI_{fat} group across trial was significant for CH_4 and CO_2 emission and yield for both heifers and cows (Table 3). Low RFI_{fat} heifers emitted 2.5% less CH_4 and 1.4% less CO_2 ($P<0.001$) compared with high RFI_{fat} heifers, while low RFI_{fat} cows emitted 3.7% less

CH_4 and 3.4% less CO_2 ($P<0.001$) compared with high RFI_{fat} cows. However, low RFI_{fat} heifers and cows had higher CH_4 and CO_2 yield ($P<0.001$) per kg of DMI but were similar for CO_2/CH_4 ratio. Other researchers using different techniques such as SF_6 (Hegarty et al. 2007; Fitzsimons et al. 2013), RC and GEM system (Alemu et al. 2017) also reported that low RFI_{fat} heifers had lower feed intake and emitted less daily CH_4 compared with high RFI_{fat} heifers. Recent studies (Hegarty et al. 2007; Fitzsimons et al. 2013; Alemu et al. 2017) are inconsistent in CH_4 yield depending on the method of measurement, diet composition and definition of methane yield. Contradictory to our results, Fitzsimons et al. (2013) reported higher CH_4 yield for high RFI Simmental heifers when CH_4 yield was expressed as g CH_4 kg $BW^{-0.75}$ (2.9 vs. 2.5; n=28). Whereas, Alemu et al. (2017) reported no difference in CH_4 yield for low RFI_{fat} compared with high RFI_{fat} heifers when CH_4 yield was expressed as g CH_4 kg DMI^{-1} using GEM and RC (GEM, 27.7 vs. 28.5, n=16, $P > 0.25$; RC, 26.5 vs. 26.5; n=16, $P > 0.99$). Hagerty et al. (2007) reported lower CH_4 yield for low RFI steers (n=20) such that low RFI cattle emitted 41.2 g less CH_4 per unit of ADG.

Lower CH_4 and CO_2 emission (g d^{-1}) in low RFI_{fat} heifers and cows appears to be partially due to lower feed intake compared with their high RFI_{fat} pen mates and is reflected by the high positive phenotypic correlations ($r_p = 0.85$ to 0.89; $P < 0.001$) between CH_4 and CO_2 emission and DMI (Herd et al. 2014; Manafiazar et al. 2017), and moderate negative phenotypic correlations ($r_p = -0.36$ and -0.77, $P < 0.001$) between CH_4 and CO_2 yield and DMI (Manafiazar et al. 2017). Potts et al. (2017) recently reported that 9 to 31% of the variation in RFI, when dairy cows are fed low starch diet, can be explained due to the animal's digestive ability, suggesting that low RFI animals had higher digestibility capacity. Bonilha et al. (2017) also reported that low RFI beef heifers achieved higher digestibility of NDF ($P = 0.001$) and TDN ($P = 0.066$).

These associations between RFI and DMI, and higher digestibility in low RFI animals could explain our results such that low RFI_{fat} animals are more efficient in utilizing feed by having longer rumen retention time, increased DM and protein digestibility, resulting in more substrate hydrogen ions available for methanogenesis and consequently higher CH_4 and CO_2 yield, but lower daily CH_4 emissions. In addition, lower DMI and changing rumen retention time may also impact the proportions of microbial populations present with the protozoal populations that support the methanogens being relatively more sensitive to higher passage rates.

Climate Variables and DMI, CH4, CO2, and Visit Frequency

Ten of 14 trials were performed where average daily ambient temperature was below 0^{o}C, and animals experienced temperatures below -20^{o}C in 12 trials (Figures 3 and 4). Heat loss from animals is higher when lower air temperature is accompanied by wind, and is referred to as wind chill (Tarr 2015). Average daily wind chill during the CH_4 and CO_2 measurement periods by trial at the KIN and LRDC are illustrated in Figures 3 and 4, respectively, for heifers and cows. Lower critical temperature (LCT) is defined as the temperature below which animals must increase their metabolic rate from the basal point to maintain homeostasis and core body temperature. The LCT for beef cows is variable and depends on cow's age, hair depth, thickness and condition, hide thickness, backfat thickness, feed type and availability of shelter (National Research Council 2016). Lower critical temperature of -8^{o}C was reported for mature cows with dry and heavy winter coats, whereas a LCT of -34.1^{o}C was reported for steers with about 1 kg of ADG (Block et al. 2001). Scatter plots between wind chill and DMI (a), CH_4 emission (b), CO_2 emission (c), and visit frequency to GEM (d) for heifers and cows are presented in Figures 5 and 6, respectively. Scatter plots between ambient temperature and these same variables showed the same pattern as with wind chill index and are not shown. Heifers and cows had different DMI response to wind chill index. For example, heifers decreased their DMI with decreasing wind chill index between +20 and -15°C, but increased their DMI when wind chill decreased further. Regression analysis of heifer data revealed that with 1 unit decrease in wind chill index above -15°C, the amount of DMI decreased 43 g (β_1 = 43 (9) g, R^2 = 0.38, $P < 0.001$). Whereas, the relationship is changed below -15°C such that 1 unit decrease in wind chill index increased DMI by 32 g (β_1 = 32 (29) g, R^2 = 0.08, $P > 0.28$) though the linear relationship was not significant. However, cows generally increased their DMI with decreasing wind chill index (Figure 6a). Regression analysis showed that in cows a 1 unit decrease in wind chill index increased DMI by 24 g (β_1 = 24 (14) g, R^2 = 0.09, $P > 0.09$). Further regression analysis revealed that the interaction between RFI_{fat} group and wind chill index were not significant for heifers (P= 0.08) and for cows (P=0.62), thus indicating that low and high RFI_{fat} heifers and cows had similar DMI responses to wind chill index.

Methane and CO_2 emission declined as wind chill index decreased in both heifers and cows (Figures 5b, 5c, 6b and 6c). Regression analysis revealed that with 1 unit decrease in wind chill index the amount of CH_4 decreased 1.03 g (β_1 = 1.0 (0.2) g, R^2 = 0.48, $P < 0.001$) in heifers and 2.3 g (β_1 = 2.3 (0.3) g, R^2 = 0.62, $P < 0.001$) in cows. High and low RFI_{fat} mature cows had the same ($P > 0.62$) response in CH_4 reduction per one unit decrease in wind chill index, but high RFI_{fat} heifers emitted more CH_4 compared to low RFI_{fat} heifers in response to one unit decrease in wind chill index (1.37 g vs. 0.87 g, P<0.024). Regression analysis also showed that with 1 unit decrease in wind chill index the amount of CO_2 decreased 37 g (β_1 = 37 (5) g, R^2 = 0.53, $P < 0.001$) in heifers and 59 g (β_1 = 59 (12) g, R^2 = 0.42, $P < 0.001$) in cows. High and low RFI_{fat} mature cows had the same ($P > 0.62$) response of CO_2 reduction to 1 unit decrease in wind chill index. However, high RFI_{fat} heifer had a two-fold reduction in CO_2 production in response to 1

^{o}C decrease in wind chill index (52.2 g vs. 26.8 g, $P < 0.021$). Visit frequency to GEM system was also affected by wind chill index such that peak of visit occurred at about 0 ^{o}C and -10 ^{o}C of wind chill index for heifers and cows, respectively (Figures 5 and 6, d).

Generally, voluntary DMI increases as air temperature decreases (National Research Council 2016), and negative association between ambient temperature and DMI (-0.19) has been reported in steers (Milligan and Christison 1974). We observed the same trend in mature cows consuming a triticale silage diet at LRDC and a barley silage diet at KIN. However, the opposite effect was observed in heifers above -15^{o}C consuming a barley silage:barley grain diet (90:10% as fed). This could be due to a chronic versus acute exposure such that intake drops in response to temperature and encouraged heifers to look for shelter then increase their DMI. It appears that cows had experienced the cold temperature before and were able to better manage the cold stress. Factors other than ambient temperature may also affect the animals' performance such as feed type and shelter accessibility. Webster et al. (1970) reported that ad libitum fed cattle are not affected by Canadian prairie winter temperature when dry and sheltered from wind. It is also reported that digestibility of feedstuffs is reduced at lower environmental temperature along with reduced voluntary feed intake (Milligan and Christison 1974). Methane and carbon dioxide emissions are proportional to DMI, and it is expected that CH_4 and CO_2 emissions will increase with increasing DMI. In this study, we observed reduction in CH_4 and CO_2 emissions despite increasing DMI for cows and heifers at wind chill indexes below -15^{o}C. It is generally assumed that colder air temperature increases DMI, ruminal passage rate and this may reduce daily CH_4 emissions and yields (McAllister et al. 1996). Low RFI_{fat} heifers had lower reduction of CH_4 and CO_2 in response to 1 ^{o}C decrease in wind chill index compared to high RFI_{fat} without significant differences in DMI response. This may be indicative of low RFI_{fat} heifers having a lower passage rate and higher digestibility than high RFI_{fat} heifers, which is worthy of further investigation.

CONCLUSION

Efficient (low RFI_{fat}) beef heifers and cows emitted less CH_4 and CO_2 (g d^{-1}) but had higher CH_4 and CO_2 yields (g kg^{-1} DMI) compared with their high RFI_{fat} pen mates. These results further confirm that selecting and breeding animals for low RFI_{fat} has the potential to decrease greenhouse gas emissions from beef cattle production. These results also confirm that the mitigation potential is feasible in cold environments.

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Table 1. Number of animals, diet ingredient and nutrient composition by animal type, location and trial for animals tested for residual feed intake (RFI) and measured for enteric methane and carbon dioxide emissions using the Greenfeed Emissions Monitoring (GEM) system.

	Yearling heifers								Mature cows					
Location[a]	LRDC			KIN					LRDC			KIN		
Trial	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Start year of test	2015	2016	2017	2015	2015	2016	2016	2017	2015	2016	2017	2015	2016	2017
Start date	19 Feb	22 Dec	18 Jan	5 Jan	15 Dec	10 Mar	7 Dec	13 Mar	17 Nov	19 Oct	18 Oct	17 Nov	22 Nov	15 Nov
Days on test	75	72	114	78	76	75	84	81	86	84	84	77	79	82
Number of animals	86	103	114	225	145	150	149	163	20	20	21	40	40	40
Groups in GEM	1	1	3	1	1	1	1	2	1	1	1	1	1	1
Animals monitored by GEM														
High RFI	14	8	45	17	16	16	15	16	6	6	7	16	16	18
Low RFI	12	5	38	31	13	20	13	35	5	8	7	15	18	17
Diet ingredient composition, as fed basis														
Barley silage, %	90.0	100.0	90.0	55.0	55.0	55.0	78.0	88.2	---	---	---	95.0	85.0	85.0
Barley grain, %	10.0	0.0	10.0	---	---	---	---	---	---	---	---	---	10.0	10.0
Protein supp., %	---	---	---	5.0	5.0	5.0	4.0	2.4	---	---	---	5.0	5.0	5.0
Whole Oat, %	---	---	---	27.0	27.0	27.0	6.0	---	---	---	---	---	---	---
Canola Meal, %	---	---	---	13.0	13.0	13.0	---	---	---	---	---	---	---	---
Triticale silage, %	---	---	---	---	---	---	---	---	100.0	100.0	100.0	---	---	---
Corn DDGS, %	---	---	---	---	---	---	12.0	9.4	---	---	---	---	---	---
Nutrient composition[b], % DM														
TDN, %	63.3	63.5	62.5	67.1	70.1	67.2	69.3	68.9	57.5	59.5	59.5	60.6	61.8	66.7
Crude protein, %	12.5	11.4	13.3	19.0	19.4	15.9	17.6	17.5	9.9	11.9	11.9	13.9	14.4	14.3
ADF, %	29.1	30.9	32.9	24.2	22.6	26.8	26.3	27.9	37.1	35.3	35.3	31.4	28.4	25.9
NDF, %	44.5	46.6	49.5	35.8	35.1	41.3	42.0	40.9	52.0	49.8	49.8	46.1	43.7	37.8
Calcium, %	0.60	0.46	0.69	1.2	0.93	0.85	0.86	1.08	0.34	0.32	0.32	1.23	1.23	1.35
Phosphorous, %	0.34	0.29	0.31	0.51	0.51	0.39	0.47	0.48	0.25	0.27	0.27	0.31	0.35	0.32

[a] LRDC refers to the Lacombe Research and Development Centre, while KIN refers to the Roy Berg Kinsella Research Station.

[b] TDN, ADF and NDF refers to total digestible nutrients, acid detergent fibre and neutral detergent fibre, respectively.

Table 2. Least squares means for performance traits in replacement beef heifers (8 trials) and mature cows (6 trials) during feed intake testing at Lacombe Research and Development Centre and the Roy Berg Kinsella Research Station.

Performance traits	Overall n	Mean (SD)	Residual feed intake, adjusted for off-test backfat (RFI$_{fat}$) High	Low	SE[a]	P value	P values for main effect and interaction Trial	Trial x RFI$_{fat}$
All heifer during feed test periods (75-114 d)								
Number of heifers			540	528				
On-test age, d	1068	278 (45)	283	282	1.1	0.807	<0.044	0.513
Test mid-point weight, kg	1068	352.9 (45.0)	357.3	357.6	1.4	0.869	<0.001	0.967
Test ADG, kg d^{-1}	1068	1.05 (0.25)	1.02	1.02	0.00	0.575	<0.001	0.693
Off-test backfat, mm	1068	5.5 (2.2)	5.8	5.7	0.08	0.686	<0.001	0.934
Test RFI$_{fat}$, kg DM d^{-1}	1068	0.00 (0.52)	0.38	-0.40	0.01	<0.001	0.356	<0.001
Heifers that visited the Greenfeed Emissions Monitoring system during feed test periods								
Number of heifers			147	167				
On-test age, d	314	291 (40)	287	287	1.3	0.910	<0.001	0.009
Test mid-point weight, kg	314	269.8 (43.3)	368.7	368.4	2.4	0.928	<0.001	0.970
Test ADG, kg d^{-1}	314	1.01 (0.21)	1.02	1.01	0.01	0.771	<0.001	0.427
Off-test backfat, mm	314	5.8 (2.3)	6.1	5.8	0.2	0.201	<0.001	0.019
Test RFI$_{fat}$, kg DM d^{-1}	314	-0.05 (0.48)	0.34	-0.39	0.03	<0.001	0.963	0.742
Cow during feed test periods (77-86 d)								
Number of cows			84	92				
On-test age, yr	176	4.0 (2.2)	4.6	4.6	0.1	0.899	<0.001	0.447
Test mid-point weight, kg	176	651 (92.5)	678.6	674.7	7.8	0.628	<0.001	0.852
Test ADG, kg d^{-1}	176	0.95 (0.29)	0.89	0.88	0.03	0.848	<0.001	0.989
Off-test backfat, mm	176	9.8 (4.5)	10.9	10.7	0.05	0.640	<0.001	0.327
Test RFI$_{fat}$, kg DM d^{-1}	176	0.00 (0.67)	0.59	-0.52	0.06	<0.001	0.777	0.003
Cows that visited the Greenfeed Emissions Monitoring system during feed test periods								
Number of cows			69	70				
On-test age, yr	139	3.5 (2.1)	4.1	4.3	0.2	0.443	<0.001	0.913
Test mid-point weight, kg	139	638 (86)	678.1	669.2	9.7	0.358	<0.001	0.917
Test ADG, kg d^{-1}	139	0.99 (0.26)	0.92	0.90	0.04	0.613	<0.001	0.884
Off-test backfat, mm	139	9.2 (3.9)	10.5	10.5	0.6	0.986	<0.001	0.997
Test RFI$_{fat}$, kg DM d^{-1}	139	0.00 (0.71)	0.63	-0.58	0.08	<0.001	0.963	0.004

[a] Standard error of mean differences

Table 3. Least squares means of feeding behaviour, and methane and carbon dioxide production traits in replacement heifers (8 trials) and mature cows (6 trials) during feed intake testing at Lacombe Research and Development Centre and the Roy Berg Kinsella Research Station

Traits	Overall n	Mean (SD)	Residual feed intake, adjusted for off-test backfat (RFI_{fat})				P values for other main effects, interactions and covariates				
			High	Low	SE[a]	P value	Trial	Trial x RFI_{fat}	Day	Visit	Visit time
Heifer daily observations during methane measurement (24-62 d)											
Feed intake, kg DM d^{-1}	6789	8.17 (1.82)	8.48	7.80	0.05	<0.001	<0.001	0.045	<0.001	-----	-----
Feeding duration, min d^{-1}	8456	140.6 (45.7)	131.9	123.8	1.2	<0.001	<0.001	<0.001	<0.001	-----	-----
Feeding headdown, min d^{-1}	8456	97.4 (38.3)	92.4	77.2	1.1	<0.001	<0.001	<0.001	<0.001	-----	-----
Feeding frequency, events d^{-1}	8456	66.5 (39.8)	65.3	55.3	0.75	<0.001	<0.001	<0.001	<0.001	-----	-----
GEM visits, visits d^{-1}	9099	2.75 (1.53)	2.88	2.58	0.03	<0.001	<0.001	<0.001	<0.001	-----	-----
GEM visit time, min d^{-1}	9099	12.36 (7.3)	13.3	12.1	0.2	<0.001	<0.001	<0.001	<0.001	-----	-----
GEM pellet intake, kg d^{-1}	9095	0.52 (0.21)	0.49	0.45	0.07	<0.001	<0.001	<0.001	<0.001	-----	-----
CH_4 emission, g d^{-1}	9099	178.9 (47.2)	184.1	179.7	1.2	0.001	<0.001	<0.001	<0.001	0.221	0.059
CO_2 emission, g d^{-1}	9099	6105 (1364)	6317	6230	28	0.001	<0.001	<0.001	<0.001	0.319	0.006
CH_4 yield, g kg^{-1} DMI	6789	22.8 (7.2)	22.7	24.1	0.20	<0.001	<0.001	<0.001	<0.001	0.369	0.169
CO_2 yield, g kg^{-1} DMI	6789	771 (211)	785	842	6.3	<0.001	<0.001	<0.001	<0.001	0.715	0.237
CO_2/CH_4 ratio, g d^{-1}	9099	35.5 (8.8)	35.7	36.0	0.18	0.159	<0.001	<0.001	<0.001	0.997	0.205
Cow daily observations during methane measurement (33-54 d)											
Feed intake, kg DM d^{-1}	4069	12.69 (2.65)	13.16	11.64	0.08	<0.001	<0.001	<0.001	<0.001	-----	-----
Feeding duration, min d^{-1}	4073	171.6 (74.1)	147.8	140.1	1.9	<0.001	<0.001	<0.001	<0.001	-----	-----
Feeding headdown, min d^{-1}	4073	104.8 (49.3)	104.6	100.9	1.6	0.02	<0.001	<0.001	<0.001	-----	-----
Feeding frequency, events d^{-1}	40731	76.0 (30.4)	75.4	70.6	0.8	<0.001	<0.001	<0.001	<0.001	-----	-----
GEM visits, visits d^{-1}	4694	2.40 (1.23)	2.28	2.21	0.04	0.135	<0.001	0.011	<0.001	-----	-----
GEM visit time, min d^{-1}	4702	10.12 (5.50)	9.63	9.32	0.17	0.116	<0.001	0.002	<0.001	-----	-----
GEM pellet intake, kg d^{-1}	2810	0.50 (0.23)	0.45	0.42	0.09	0.003	<0.001	0.002	<0.001	-----	-----
CH_4 emission, g d^{-1}	4694	237.5 (69.4)	241.2	232.7	2.3	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CO_2 emission, g d^{-1}	4694	8417 (1836)	8145	7875	51	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CH_4 yield, g kg^{-1} DMI	4061	19.52 (7.2)	19.2	21.1	0.2	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

CO_2 yield, g kg^{-1} DMI	4061	685 (208)	640.8	703.6	6.5	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CO_2/CH_4 ratio, g d^{-1}	4694	37.1 (8.6)	35.5	36.0	0.3	0.045	<0.001	<0.001	<0.001	0.031	<0.001

[a] Standard error of mean differences

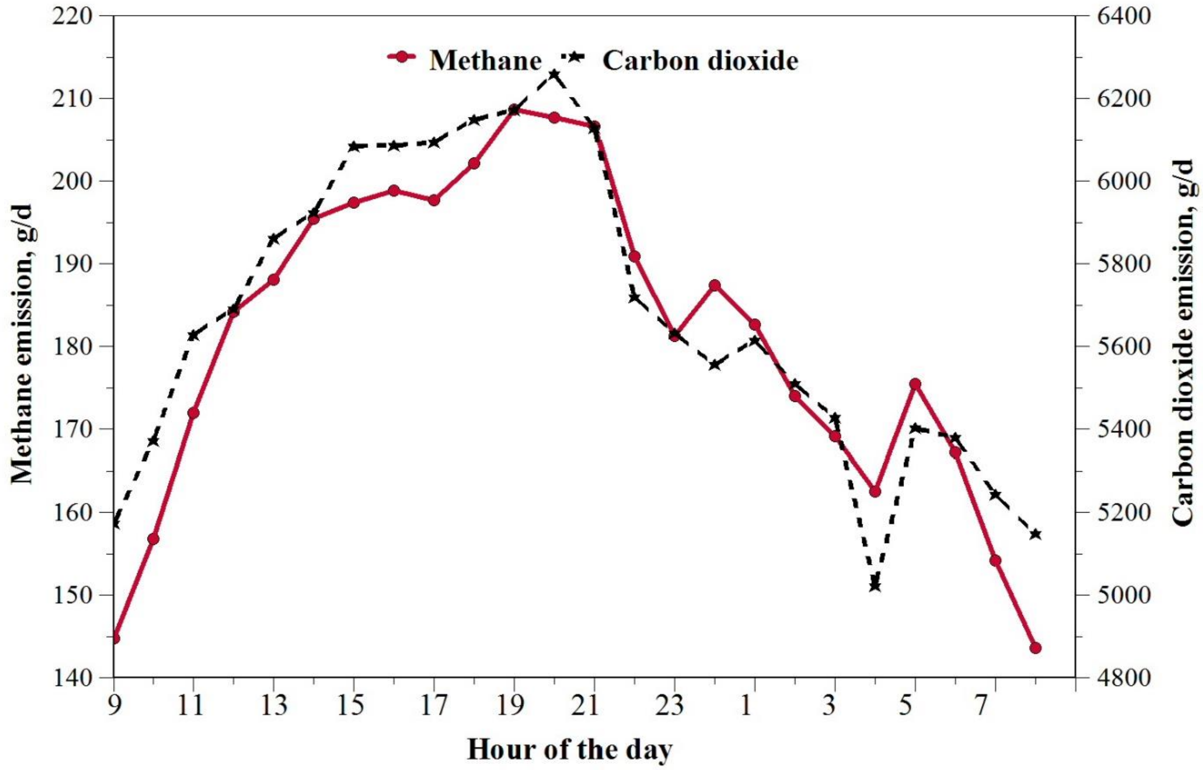

Figure 1. Diurnal distribution of enteric methane and carbon dioxide emissions from replacement beef heifers fed a high forage diet in drylot as measured by the GreenFeed Emission Monitoring system.

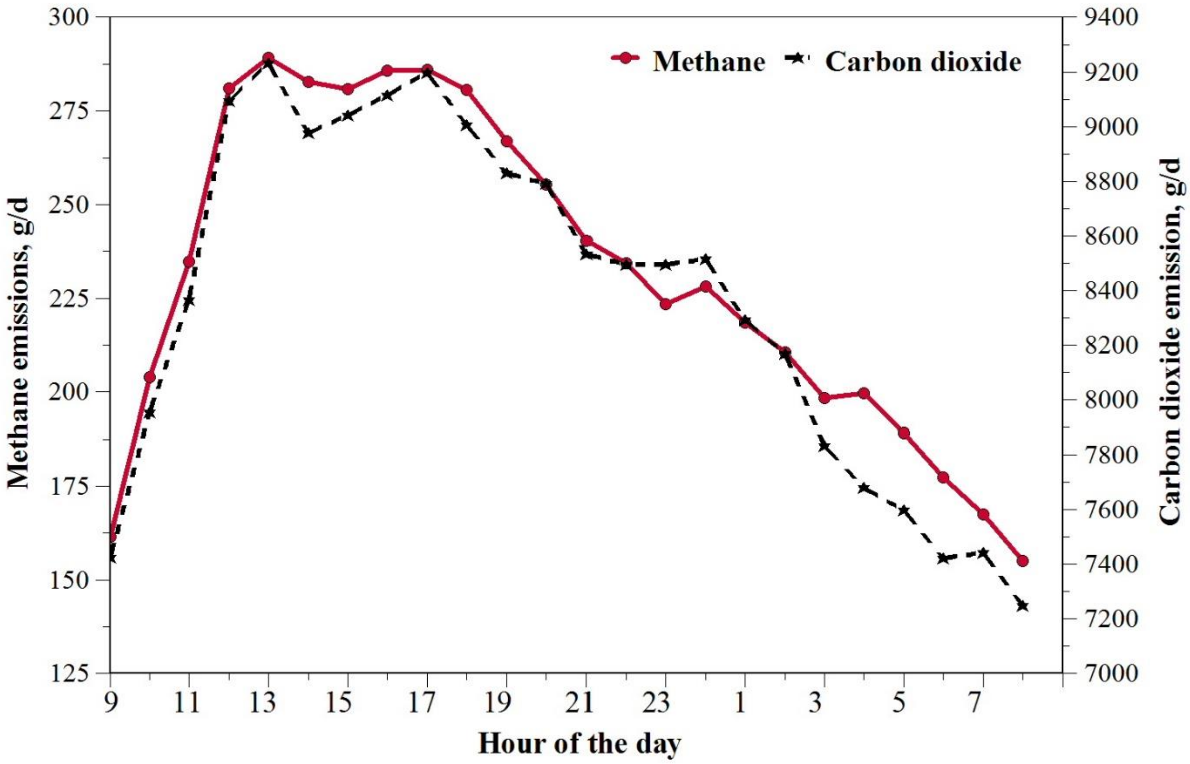

Figure 2. Diurnal distribution of enteric methane and carbon dioxide emissions from cows fed a forage diet in winter drylot as measured by the GreenFeed Emission Monitoring system.

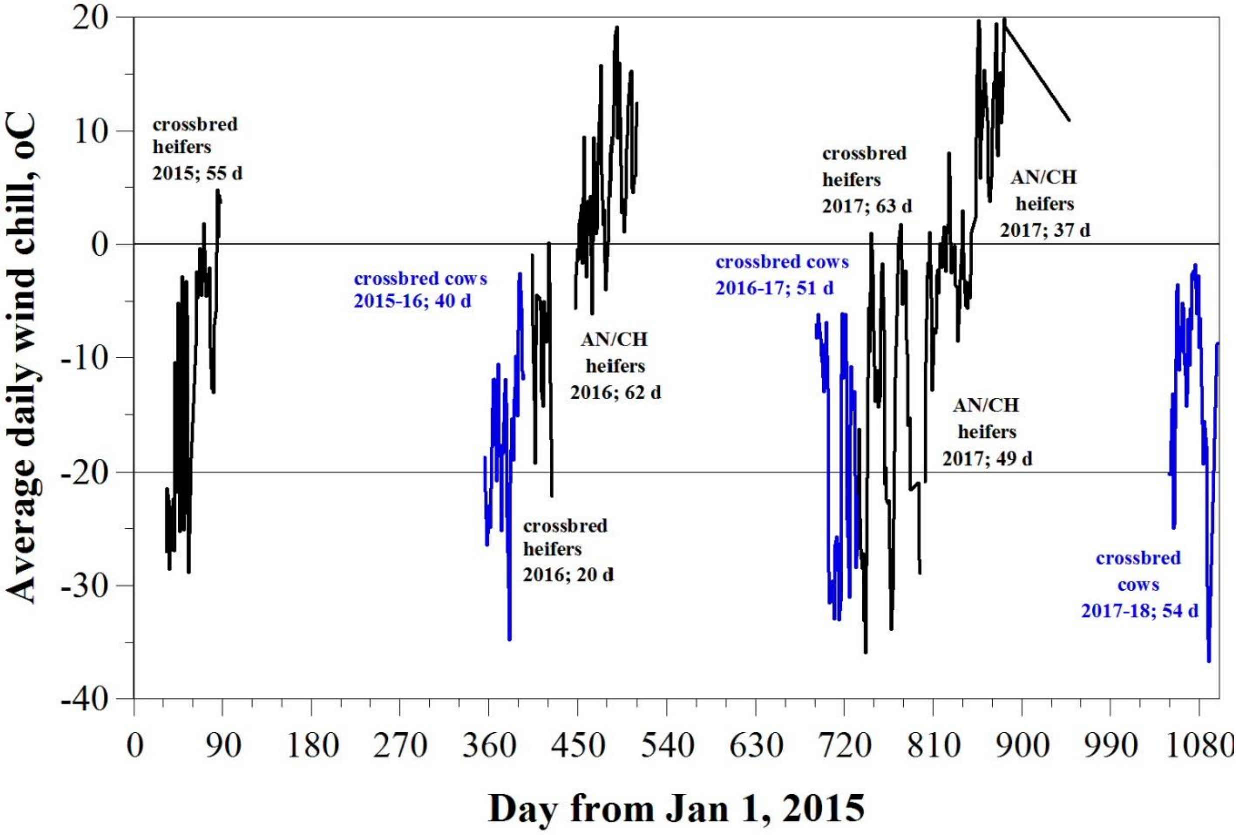

Figure 3. Average daily wind chill during GreenFeed Emission Monitoring system measurements by trial at the Roy Berg Kinsella Research Station during the winters of 2015 to 2017. Black solid lines are heifers while blue solid lines are cows. There were 14, 12, 1, 0, 19, 23, 1 and 9 d where daily wind chill averaged below -20 ^{o}C for 2015 KIN heifers at KIN, 2015-16 cows KIN, 2016 KC heifers, 2016 Angus/ Charolaise heifers, 2016-17 KC cows, 2017 KC heifers, 2017 AN/CH heifers and 2017-18 KC cows, respectively.

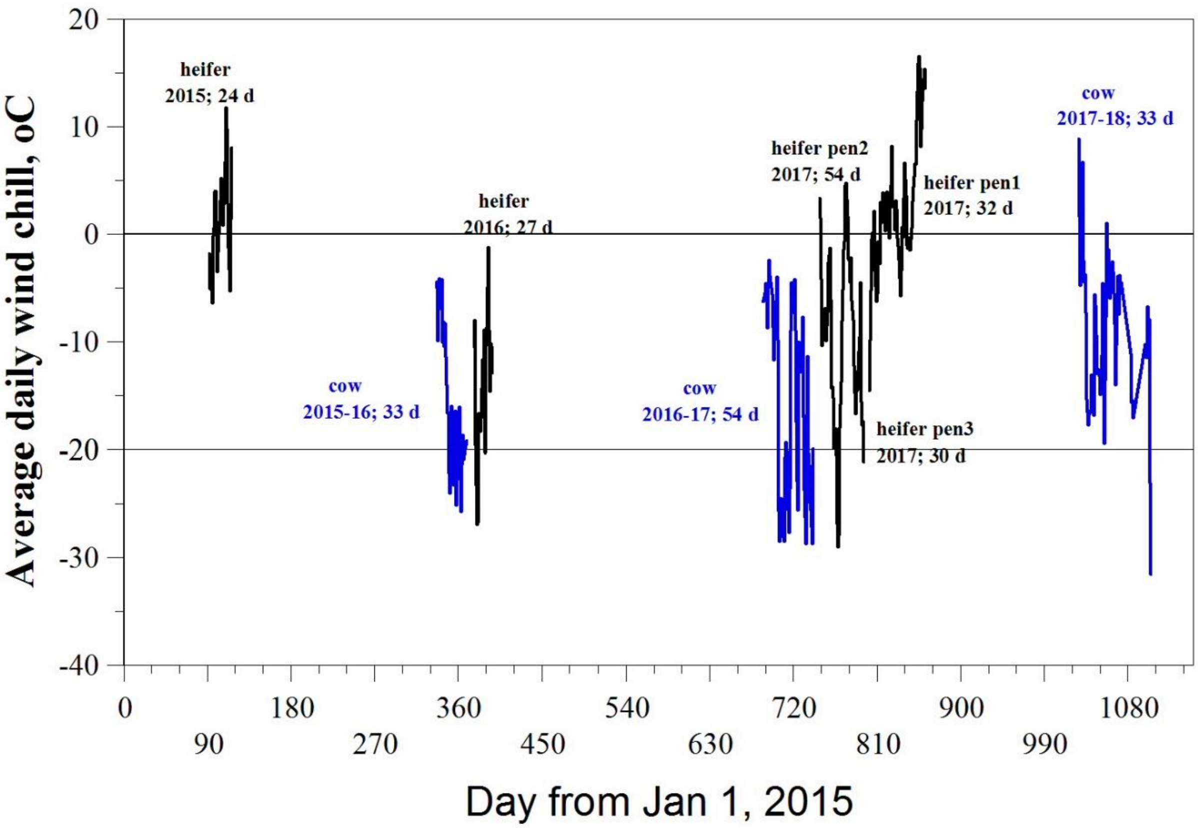

Figure 4. Average daily wind chill during Greenfeed Emission Monitoring system measurements by trial at the Lacombe Research and Development Centre during the winters of 2015 to 2017. Black solid lines are heifers while blue solid lines are cows. There were 0, 11, 3, 21, 5, 0, 0, and 1 d where daily wind chill averaged below -20 ^{o}C for 2015 heifers, 2015-16 cows, 2016 heifers, 2016-17 cows, 2017 pen 2 heifers, 2017 pen 3 heifers, 2017 pen 1 heifers and 2017-18 cows, respectively.

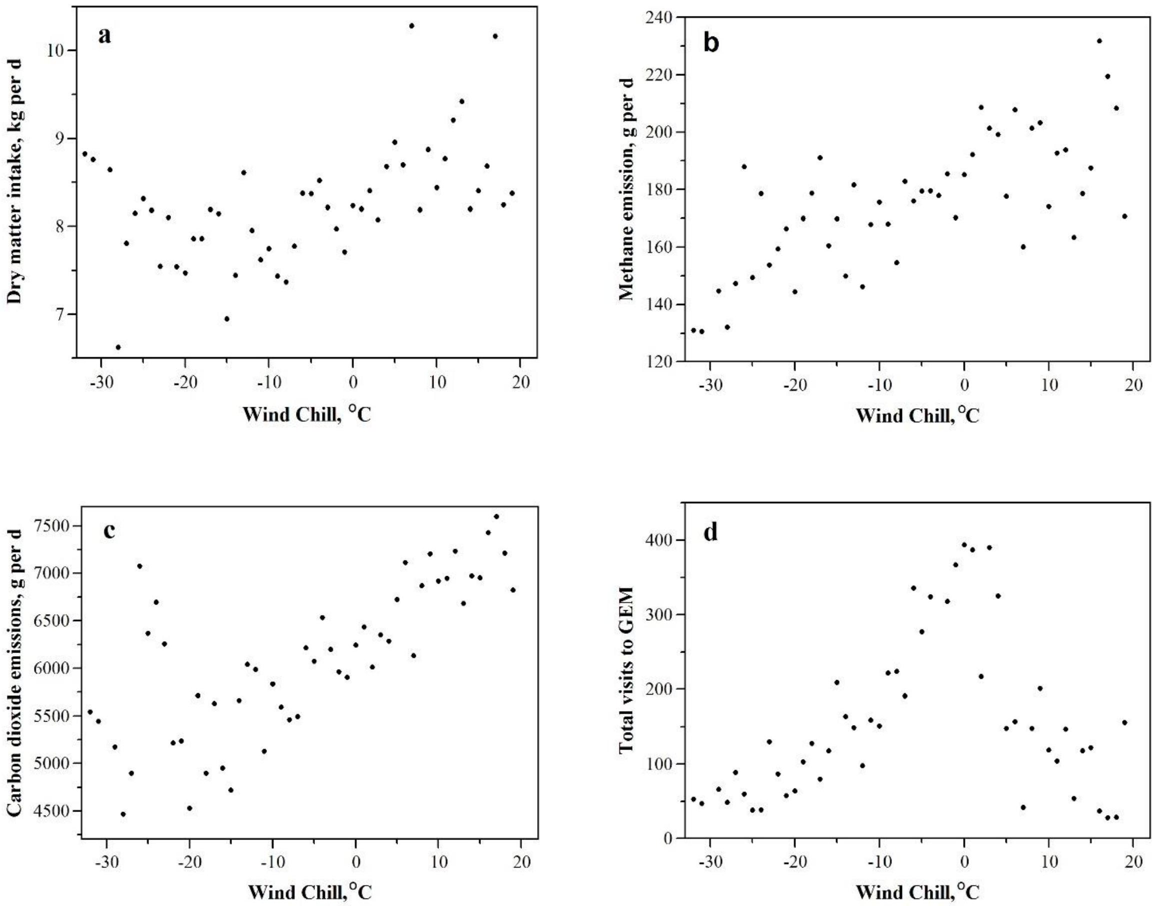

Figure 5. Scatter plot of wind chill index versus average daily dry matter intake (a), average daily methane (CH_4) emission (b), average daily carbon dioxide (CO_2) emission (c), and number of visits per day in replacement heifers. Each point is the mean across animals and days for a particular wind chill index.

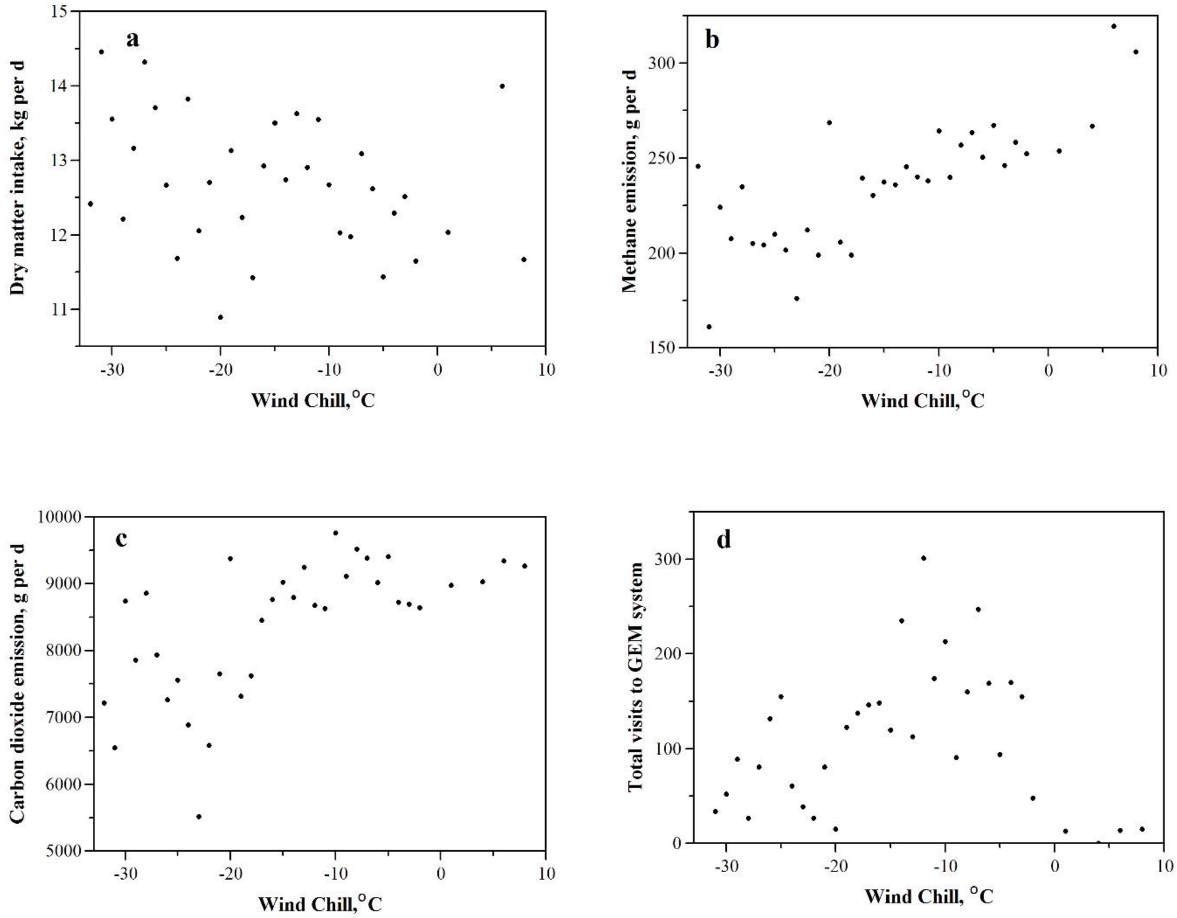

Figure 6. Scatter plot of wind chill index versus average daily dry matter intake (a), average daily methane (CH_4) emission (b), average daily carbon dioxide (CO_2) emission (c), and number of visits per day in mature cows.