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Greenhouse Gas Emissions From Two Contrasting Beef Systems from Birth to Slaughter in Eastern Nebraska

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GREENHOUSE GAS EMISSIONS FROM TWO CONTRASTING BEEF SYSTEMS FROM BIRTH TO SLAUGHTER IN EASTERN NEBRASKA

by

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GREENHOUSE GAS EMISSIONS FROM TWO CONTRASTING BEEF SYSTEMS FROM BIRTH TO SLAUGHTER IN EASTERN NEBRASKA

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University of Nebraska, 2021
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Over the last 15 years, the increase in land use for corn and soybean has come at the expense of acres of grasslands and perennial forages employed in conventional beef-production systems. Implementing alternative cow-calf production systems into existing cropping systems may be a solution for reduced land availability and reducing total greenhouse gas emissions (GHG). Therefore, GHG from a conventional (CONV) pasture-based cattle production system with cows wintered on corn residue and summer grazing of brome pasture were compared to partial-confinement system (ALT) with cows and calves in a drylot during the summer and grazing cover crops and corn residue over the fall and winter. Eddy covariance and pen chambers were used to measure emissions from grazing and confinement scenarios. Measured CH_4 and modeled N_2O emissions totaled 7.5 ± 0.3 and 7.4 ± 0.3 kg CO_2e kg^{-1} HCW for CONV and ALT production, respectively. There was a measured uptake of 233 g C m^{-2} and 98 g C m^{-2} from brome pasture and cover crop, respectively. Accounting for CH_4 and N_2O emissions using global warming potential (GWP) of 23 and 298 resulted in a net sink of 0.7 ± 0.2 kg CO_2e kg^{-1} HCW for CONV and a net source of 16.7 ± 1.5 kg CO_2e kg^{-1} HCW for ALT. The same calculations using global warming potential (GWP) of 4 and 234 resulted in a net sink of 10.9 ± 1.0 kg CO_2e kg^{-1} HCW for CONV and a net source of 7.1 ± 1.5 kg CO_2e kg^{-1} HCW for ALT. Carbon sequestration from perennial grasslands in the CONV was enough to offset all emissions and biogenic $CO_{2.}$ Annual forage grazed in the ALT system offset 42 to 72% of systems emissions depending on GWP metric used. These net carbon results open new horizons to livestock carbon balance research and give evidence that grazing systems sequester carbon emissions from cattle and in some cases are a carbon sink.

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allowed to flourish. It is humbling to be able to contribute to that work, and I feel privileged to be a part of it. For me, most importantly, I accept the award of a PhD, not for myself, but for every person God will place in my path the rest of my career. I owe it to everyone to share what I have learned and use it for the prosperity of all I work with and work for. It's not a Ph.D. for me, but for them.

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Introduction

The global carbon balance as it affects the earth's longwave radiation balance is perceived to be the cause of increasing global temperatures resulting in rapid changes in weather patterns and sea levels. Scientists theorize increasing levels of atmospheric carbon and nitrogenous gases that trap radiant heat the cause. Emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the primary drivers and focus of research. The burning of fossil fuels relocates approximately 51 Gt of carbon annually into the atmosphere (Masson-Delmotte et al., 2018), but emissions from food production have taken particular interest from scientists and policy makers alike. This review attempts to summarize the sources and measurement techniques of CO_2, CH_4 and N_2O from beef production. Recent discoveries in carbon I sequestration and models of greenhouse gas (GHG) production will be presented to describe a framework and focus for future research.

Agriculture is a primary industry to interact with the C cycle and accounts for 34% of all emissions worldwide. Those levels in industrialized nations (24%) have remained steady since 1990 despite a 40% increase in food production during that time (Crippa et al., 2021). In addition, industrialized nations have already leveled off non-CO_2 (CH_4 and N_2O) emissions since 1990 at 20 Gt per year. In developing countries, emissions from the food system decreased from 68% in 1990 to 39% in 2015, but this was mostly due to increases in GHG emissions (35 to 55 GT per year) from other sources such as transportation (Crippa et al., 2021). Livestock emissions are responsible for 17% of all methane emissions (IPCC 1992).

Across the globe the world beef cattle population was 1.4 billion in 2010. That was distributed 25% in Latin America, 25% in Asia, 20% in Africa, 10% in North America, 6% in the EU, 3% in Oceania, and 6% in the Middle East (FAO stat 2012). The United States produces 20% of the worlds' beef with 7% of the world's cattle population (Capper 2011). Capper (2011) conducted a historical analysis of beef production in the U.S. by comparing 1977 with 2007 beef production. From 1977 to 2007 there was a 20% reduction in the number of days required to grow animals from birth to slaughter and in 2007, per unit of beef produced it required 12% less feed energy. The supporting herd population also decreased. An important part of this improvement was the adoption of finishing cattle in feedlot systems with high energy diets. Grass finished beef produces more GHG per unit of product and requires more time and feed resources (Desjardins et al., 2012) and grass finished cattle require approximately 226 more days to reach equal market weight (Capper 2011)

The North American ruminant population has transitioned from the bison herd which roamed the plains for thousands of years. Domestic cattle have replaced those herds and there is considerable interest in how that has affected the environment. Kelliher and Clark (2010) studied changes in CH_4 production both before and after the settlement of the U.S. in the 18th and 19th centuries. They estimated the bison herd as 30 million hd producing 2.2 Tg CH_4 per year compared to 2.5 Tg CH_4 per year in the current cattle herd. Others report that 60 million bison roamed north America and produced 228 billion kg of CO_2e (Capper and Hayes, 2012). In 2007, the U.S. dairy industry produced

112 billion kg CO_2e (Capper, 2009b) and beef industry produced 213 billion kg CO2e annually. Hristov (2012) modeled wild ruminants in North America pre and post European settlement. Bison, elk and deer CH_4 emissions pre-settlement were 86% (assuming bison herd of 50 million hd) of today's emissions from domesticated ruminant animals. Present day, wild ruminants are estimated to be 4.3% emissions from the domestic herd. Understanding the history of recent estimates of livestock emissions is relevant. In 2006 the United Nations Food and Agriculture Organization reported that livestock were responsible for 1278 Tg CO_2e, 18% of global GHG emissions (Steinfeld et al., 2006). This was more than what was reported for the entire transportation industry. Later a life-cycle assessment of GHG in the U.S. showed the beef industry an all agriculture produced 3.3% and 9% of all emissions respectively. Transportation and electricity generation were responsible for 56% of all emissions (Rotz et al., 2019). Other agencies such as U.S. Environmental Protection Agency reported in 2011 that livestock are responsible for only 198 Tg CO_2e or 3.4% of all emissions (EPA, 2011). Many of the discrepancies between these and other reports is how GHG emissions and sinks are considered and calculated. Life cycle assessments of livestock have been challenging to develop for the same reason. Cederberg et al. (2011) estimated the lifecycle emissions of Brazil. As Brazilian beef production continues to expand, forests have been converted to rangeland. The loss of carbon sequestering forests increases the carbon balance. Assigning the loss in C sequestration to all rangelands over 20 years results in 44 kg CO_2e per kg liveweight (LW),but allocating to only the new rangelands increases that to 726 kg CO_2e per kg LW. Detailed descriptions of recent life cycle assessments are summarized later in this review.

Efforts have been made to standardize the measure of GHG emissions from all sources, including livestock. The Intergovernmental Panel on Climate Change (IPCC) has created standard methodologies and put them into three tiers. Tier 1 methodology calculates emissions for each country and region using animal population data and multiplying each category of livestock (bovine, swine, etc) by an emission factor (IPCC 1997). Tier 2 methodology gives more specific data by accounting for livestock weight, age, sex and diet. For example, Tier 2 methodology makes assumptions on energy losses in forage-based diets is 6.5% of GE intake and grain-based diets as 3.5% of GE (Rochette et al., 2008). Emissions (g per animal) is back-calculated from GE and the energetic value of methane (55.65 MJ/kg and 4.18 MJ/Mcal, NASEM 2016) Lastly, Tier 3 methodology takes into account differences by country, diet, changes over seasons and strategies to reduce emissions (IPCC 2006).

GREENHOUSE GASES

Greenhouse gases are an important part of the Earth's atmosphere. Earth was initially a hot mix of solids and gases with very little atmosphere. Gases from volcanic eruptions produced methane, CO_2 and H_2S. As GHG built up in the atmosphere, the radiative properties of these gases trap heat inside of Earth's atmosphere and allow for condensation of water molecules. (Neale et al., 2021). If GHG had not built up over millions of years, the average temperature of Earth would be -20°C. However, with the displacement of C into the atmosphere, this GHG effect continues to increase ambient temperatures (British Geological Survey 2021).

Each of these greenhouse gases (CO_2, CH_4 and N_2O) is assigned a global warming potential (GWP) which is the measure of how much potential energy the emissions of 1 ton of gas will absorb over a given period of time relative to the emissions of 1 ton of CO_2. These principals were first developed in the 19th century by Svante Arrhenius who observed temperature changes with varying degrees of pressure, and concentration of H_2O vapor and CO_2 gas (Arhenius 1896). The GWP values of CH_4 and N_2O hve been debated heavily since the GWP value used greatly impacts the effect each gas. Heat capture by CH_4 over a 20-year period is 84 times more potent than CO_2, but this value over 100 years is 28 (IPCC 2013). Given the 9 to 12 year lifespan of CH_4 the GWP_{100} has been questioned. In addition, new data (Allen et al., 2018; Cain et al., 2019, Place and Mitloehner, 2021; Smith et al., 2021) show that the increase in global temperatures has been less than expected given global values for CH_4 and CO_2. This is used as evidence that CH_4 is being converted to CO_2 in the atmosphere, trapping less heat, and causing cooling. This new equation is as follows:

$$CO_{2we}\,(GWP^*) = 4.53 * E100(t) - 4.25 * E100(t-20)$$

In this equation E100 is the CO_2e calculated using the traditional method of GWP_{100}. The time horizon being calculated is t. When subtracting 20 from t GWP from 20 years earlier (CO_2e) are taken into account. Use of this equation helps account for both long and short-lived pollutants and their buildup and breakdown in the atmosphere. The same debate has occurred with N_2O which traditionally was considered to have a GWP of 265 or 298. Using GWP* this drops to 234 for N_2O (IPCC 2013).

It has been noted that the concentration of CH_4 and CO_2 are highly correlated. Bai et al. (2015) measured CH_4 and CO_2 over a feedlot in Australia using a Bomem MB100 spectrometer. They found CH_4 and CO_2 concentration in the air above the feedlot had a strong positive correlation ($R^2 = 0.90$). The CH_4:CO_2 ratio is a common measure used in the literature, and Bai et al. (2015) suggests CH_4 production could be predicted by modeling CO_2 production from ME intake or heat production which are related to dietary input and activity (Madsen et al., 2010).

Methane

Of the entire food production system, methane is responsible for 35% of emissions (expressed as CO_2e) after considering all CH_4 from livestock production, farming and waste (Crippa et al., 2021). Rice is also a major source of methane and is responsible for 40% of food system emissions in countries such as Thailand and Bangladesh (Crippa et al., 2021). Methane is responsible for 55 to 92% (Verge et al., 2008, Ridoutte et al., 2011) of the carbon footprint of beef production. Methane losses are also expressed on a percent loss of gross energy intake (GEI) which ranges from 3% in finishing diets (Van Haarlem 2008) to 9.5% in high forage diets (McCaughey et al., 1999).

Establishment of Methanogens and Rumination in young calves

Methanogens are a variety of archaea species directly responsible for the production of CH_4 using CO_2 and H_2 as substrates. The inoculation of the rumen with bacteria was believed to happen at birth or immediately after birth based on the theory that the gastrointestinal tract is sterile at birth. Rey et al. (2014) measured microbial community of newborn calves 1, 2, 12, and 15 – 83 days post partum. On day 1 no bacterial community could be measured. On day 2 the 16S RNA abundance indicated 70% proteobacteria, 14% *Bacteroidetes*, and *Pasteurallaceae* was the dominant family (58%). By day 12 those abundances had changed to 21% *Bacteroidetes*, 11% *Prevotella,* 5% fusobacterium and 4% streptococcus. Solid food intake increased from day 15 to 83 at weaning. *Prevotella* had become the dominant species (42%) while many other genera had decreased or disappeared. Guzman et al. (2015) measured methanogen prevalence within 20 minutes of birth, and 24, 28, and 72 h after birth. Methanogens and fibrolytic bacteria were present at birth indicating inoculation occurred before or during birth. It is likely that methanogens in the newborn GI tract have an alternative source of hydrogen such as other bacteria through cross feeding since no feed has yet been consumed. The presence of fibrolytic bacteria at birth indicate that substrates other than cellulose and hemicellulose can be used for energy since no cellulose or hemicellulose is present in the newborn GI tract. In humans, microbial inoculation occurs when the fetus begins to swallow amniotic fluid which could be bringing in microbes from the gums and oral cavity and into the bloodstream to placenta, amniotic liquid and GIT before birth.

Meale et al. (2017) noted rapid structural and microbial changes in the rumen and intestinal lining at weaning. These changes are complex and new research shows the intricacies of the GIT and new methods (delayed weaning and step-down weaning) can make the microbial and physiological changes more gradual. At weaning, changes in substrate sensed in the lower GIT increase the nutrient permeability of the forestomach. Bi et al. (2019) measured the microbial community in young lambs. Analysis suggests those microbes in the guts of nursing lambs originated from the mother's teats (43%) and ambient air (28%). Bottle fed sheep also contained microbes in their rumens, but those originated from the mother's vagina (46%) ambient air (31%) and the sheep pen floor (12%). Zhou et al. (2014) euthanized 3- to 4-week-old calves and measured methanogen prevalence throughout the GI tract. A gradual change was observed in the microbial community as digesta was sampled from the rumen to the rectum. Total methanogens decreased (numerically, not significantly) in the small intestine and then increased in the colon and rectum. There was less diversity of methanogenic communities than what has been observed in adult cattle.

The development of rumen epithelial tissue pre-weaning is under both hormonal control and influence of environmental factors. Diao et al. (2019) stated that rumen epithelial cell proliferation was induced hormonally by insulin (75%), epidermal growth factor (97%), and IGF1 (96%). Management techniques can be used to increase epithelium development and microbial population growth by 1) liquid feed help develop the SI and papillae length, 2) Starter feed – fermentable CH_2O feeding increases VFA production which stimulates rumen epithelium but excessive amounts can cause rumen acidosis 3) Fiber – help develop rumen wall thickness – mixed results on animal performance and GIT development when debating starter feed concentrate vs fiber 4) greater fiber length 5) probiotics and 6) plant extracts (Diao et al.,2019). In conjunction with methanogen prevalence, rumination increases as milk intake decreases and feed intake increases (Tedeschi and Fox, 2009). Van Ackeren et al. (2009) compared feeding total mixed rations of either 30 (H30) or 40% (H40) roughage to early weaned cannulated Holstein calves. New methods of rumination sensing technology were used to measure chewing and rumination behavior. Calves chewed 40,000 to 50,000 times daily at 15 weeks of age. Time ruminating per day was already 377 to 453 min at 9 weeks of age. Calves fed H30 chewed 440 boluses per day and H40 chewed 510 boluses per day. Time spent chewing was 613 to 750 min in H30 and 650 to 750 min in H40. Calves fed the H40 diet produced more acetate and H30 calves had more observed pH values < 6.0 likely caused by low roughage levels. Small differences in roughage level can greatly impact rumination activity and chewing behavior.

Estermann et al. (2002) measured CH_4 production in Angus and Simmental calves in respiration calorimeters at 1, 4, 7, 10 months of age. Methane production increased from 18, 21, 25, and 30 MJ per day. Calves consumed, on average, 1.6, 3.9, and 6.3 kg of grass hay at 4, 7, and 10 months of age. Methane production accounted for 7.8 to 8.5% of GE loss. Lockyer (1997) measured CH_4 production in crossbred beef calves (150 to 190 kg BW, 8 to 10 months of age) that produced 63.2 to 82.8 g per animal per day. Stackhouse et al. (2011) measured CO_2 and CH_4 production in Holstein calves. Bottle-fed calves (54 kg BW) produced 0 g CH_4 and 1392 g CO_2 per animal per day and starter fed calves (159 kg BW) produced 48 g of CH_4 and 5410 g CO_2 per animal per day. Tedeschi and Fox (2009) modeled calf dry feed and milk intake and growth. Milk intake and feed intake are inversely related over time.

Methanogen metabolism and the fate of rumen H

Methanogens are any species of archaea which produce methane in the rumen. These microbes have a low abundance but can decrease the energetic efficiency of the rumen and host animal by using CO_2 and H_2 ions from fermentation and using them as their primary substrate, forming CH_4 as the end product (Beauchemin et al. 2020).

Methanogens have a long generation interval (approximately 4 days) making it difficult for them to replicate quickly and compete for nutrients with other microbes (Van Soest, 1982). This is especially true for acetate. If acetolactic methanogens had a faster reproductive cycle, competition would occur for acetate which is an important VFA for the host. Methanogens can be grouped according to which electron donors are used in metabolism: hydrogenotrophic, methylotrophic or aceticlastic (Kim and Gadd 2008). Hydrogenotrophic are the most common methanogens. All these types of methanogens use CO_2 as the electron acceptor, and H_2, formate, methanol, acetate, methylamines and carbon monoxide act as electron donors (Kim and Gadd, 2008). Formate (HCOOH) is an important part of 1 carbon metabolism. It is broken up into H_2 and CO_2, the substrates for methane production. In sheep that produced less methane, acetogenesis, nitrate reduction, and fumarate reduction were all upregulated (Greening et al. 2019)

Metabolic hydrogen is released when monosaccharides are fermented to VFA, for intracellular cofactors such as NADH. Under anaerobic fermentation, cofactors must be deoxidized through hydrogenase activity and the production of H_2. Gaseous H_2 does exist in the rumen but only dissolved H_2 can be used by microorganisms (Wang et al. 2014). While multiple pathways produce H_2, buildup does not occur *in vivo* since a variety of microbes use it to reduce one-carbon molecules and CO_2, and eventually can form CH_4 (Beauchemin et al., 2020).

In the absence of CH_4 production, a greater amount of free H_2 is released and C molecules are incorporated into other rumen microbe metabolites. *In vitro* tests of this show that H_2 concentration can increase dramatically but this only represents 2.7% of the energy that would be lost if the same H_2 was used to produce CH_4. Any reduction in CH_4

makes the rumen microbial community improve energetic efficiency (Ungerfeld, 2018). Methanogenic diversity is a factor that contributes to adaptation to anti methanogenic vaccines and feed additives, decreasing their inhibition of methanogens. Some methanogens such as methanobactin utilize methanol, methylamines, and methyl sulfides in addition to CO_2 to produce CH_4 (Lieber et al. 2014). CO_2 and H_2 can also be combined to form acetate. Thermodynamically, however, this reaction is less favorable than the production of CH_4 ($\Delta G = -67.9$ and -8.7 kJ, respectively). Both nitrate and sulfate, if supplemented in the diet, can act as electron acceptors that are more thermodynamically favorable than the formation of CH_4 (Beauchemin et al., 2020).

Other H donors for methanogens include formate from Acetyl-CoA formation. Without methanogens, pyruvate is metabolized to ethanol, lactate, succinate and propionate. Lactate and ethanol are also hydrogen sinks. Then NADH is used, producing NAD, which is then shuttled back to be a H acceptor in glycolysis. When methanogens are present, less H ions are utilized for pyruvate metabolism. Instead, H ions are paired up by hydrogenase enzymes to form H_2 and with CO_2 and CH_4 is produced. Greater concentrations of H_2 have been associated with greater propionate (Wang et al. 2016). Any reduction or inhibition of pyruvate metabolism could result in an energetic loss to the animal. Inversely, decreasing CH_4 could not only redirect carbon energy losses but also make more H available and improve metabolism of the host (Beauchemin et al., 2020). These variables of microbial metabolism form the basis for the need to reduce methane to maximize energy available for the host animal

Methods of Methane Reduction

An extensive amount of research has investigated dietary methods of reducing enteric methane. Winders et al. (2020) fed growing diets at *ad libitum* intake and limited the other treatment to 75% of the intake of the control group. This reduced CH_4 by 19.2%. Beauchemin and McGinn (2006a) fed high forage (barley silage based) growing diets and high grain (barley grain based) finishing diets at both *ad libitum* and restricted (65% of ad libitum) intakes. High forage diets produced 8.5% more CH_4 per kg dry matter intake (DMI). Restriction produced 3% more CH_4 per kg DMI but 32.5% less per animal daily.

Forage level and quality can affect CH_4 production. Hales et al. (2014) fed alfalfa at 2, 6, 10, or 14% of diet dry matter in finishing diets. Methane loss was 3.07, 3.35, 3.8 or 4.18% respectively. Roughage quality also matters. Pesta (2015) fed high quality forage (60:40 blend of alfalfa and sorghum silage at 75% diet DM) and compared to low quality cornstalks (75% diet DM), both with 20% MDGS. High quality forages produced more CH_4 per day and per kg OM intake. Knapp et al. (2013) showed increased forage quality in dairy cattle diets could reduce CH_4 production by 5% per unit of milk production. Ensiled forages, which are of greater quality, also produce less CH_4 than dry forages (Sundstol, 1981)

Any unsaturated dietary fat in the rumen becomes saturated through the process of biohydrogenation. In this way dietary fat acts as a hydrogen sink making less hydrogen ions available for the production of CH_4 from CO_2 and H_2. Nagaraja et al. (1997) showed that the full scope of methane reduction occurred through three mechanisms 1) hydrogen sink through biohydrogenation, 2) increased propionate production, and 3) the addition of fat replaces less fermentable substrates that would increase methane production. Winders et al. (2020) fed corn oil at 0 or 3% of the diet DM in finishing diets. Corn oil addition reduced CH_4 per animal per day by 12.8% and reduced CH_4 per kg ADG by 17% while only reducing DMI by 3%. Hales et al. (2017) fed 0, 2, 4, and 6% corn oil in DRC based finishing diets (CP from soybean meal and no DGS). Methane production resulted in 180.5, 76, 59.3, and 55.5 g per animal per day, respectively. Alvarez-Hess et al. (2018) fed canola oil in corn or wheat based dairy diets. Oil reduced CH_4 by 11% in wheat, but there was no reduction in corn-based diets. Beauchemin et al. (2007) estimated that CH_4 production decreases 5.6% for every 1% increase in dietary fat.

Inclusion of corn byproducts can affect enteric CH_4. In theory, distillers grains reduces CH_4 due to higher fat level in both growing and finishing diets, but studies have shown mixed results. Reduction of CH_4 by DGS depends on what is being replaced in the diet. When feeding corn-based DGS, total CO_2e produced increased due to higher N_2O but CH_4 production decreased (Hunerberg et al. 2014). Hales et al. (2013) fed SFC-based finishing diets at 2x maintenance with 0 15, 30, or 45% DGS which replaced SFC. Methane production was measured using indirect calorimeter and increased with increasing DG: 69.8, 70.7, 83.1, 101.9 g per animal per day. Methane per unit of DMI was 7.8, 8.0, 9.4, or 12.7 for 0, 15, 30, or 45% DGS, respectively. The increasing CH_4 levels were likely a result of supplemental yellow grease included in the negative control diet and decreased yellow grease with increasing DGS. Resultingly, the increase in CH_4 was due to greater digestible fiber from DGS. Other studies showed reduced CH_4 in DG diets but these effects were negated due to similar fat content. Pesta (2015) using indirect calorimeters fed 0 and 40% MDGS. By product diets had no effect on CH_4 production per day or per unit feed intake. Oils have been tested with the theory of having the same effects as fat or grease. Sunflower and canola oil reduced CH_4 22% and 32% per animal per day but no reduction was measured due to essential oil (McGinn et al., 2004 and Beauchemin and McGinn 2006b). Other feed additives such as enzymes, yeast, and fumaric acid have been fed with no statistical difference in CH_4 production (McGinn et al. 2004). Various feed additives have been developed and tested as a convenient way to reduce CH_4 in non-grazing cattle. Pesta (2015) fed nitrate and sulfate in DRC:HMC blend finishing diets due to the thermodynamically favorable reduction of CO_2 with sulfate compared to the production of CH_4 and H_2 by methanogens. Sulfate and nitrate alone and combination of sulfate and nitrate did not statistically reduce CH_4 per day or per kg ADG. Fed alone sulfate and nitrate were not effective at reducing CH_4. Fed together there was a decrease in CH_4 per kg DMI. Monensin is an important feed additive that forms ion pores in the walls of gram-positive bacteria. This gives biochemical advantages to gram negative bacteria which are more likely to be propionate producers, thereby providing more gluconeogenic 3 carbon chains to the animal. This same mode of action was tested to see the effect on methanogens. McGinn et al. (2004) tested the effect of monensin on CH_4 production but found no statistical difference from negative control. Pesta (2015) found no effect of monensin on CH_4 in diets with or without MDGS.

Roque et al. (2021) fed red seaweed at 0, 0.25, and 0.5% diet DM in low, medium and high roughage diets. Red seaweed at the 0.5% inclusion reduced CH_4 59, 87, and 82% in high, medium and low forage diets, but feed intake also decreased 18, 18, and 7%, respectively. This trial was poorly replicated, and red seaweed needs more research to determine its effectiveness. Red seaweed is not currently approved to be fed to cattle since the active ingredient that reduces CH_4 is bromoform. Bromoform is considered toxic but no evidence of tissue accumulation when fed in dairy cattle (Muizelaar et al., 2021).

Vaccines have been tested as a means of mitigating CH_4. However, no vaccine can target every methanogen. Wright et al. (2004) tested effectiveness of 1st and 2nd doses of methanogen vaccines. These resulted in 6-8% reduction per animal per day and 4-5% reduction per unit DMI compared to control. A 2nd dose was administered 153 days after the first, and 28 days after the 2nd dose reductions were 12.8 per animal per day and 7.7% and per unit of DMI.. Williams et al. (2009) showed serum antibody response but no reductions in CH_4. Zhang et al. 2015 showed effectiveness of an anti-methanogen vaccine on rumen population in goats, but eventually benefits in CH_4 reduction disappeared likely due to adaption of methanogens 63 days post administration of vaccine. Future research is needed to focus on specific methanogens to increase reduction more than 20% (Martin et al., 2010).

A compound called 3Nitrooxypropanol (3NOP) is currently marketed under the trade name Bovaer and manufactured by DSM.Bovaer has been tested in backgrounding and finishing diets. Reductions in CH_4 range from 62% in a feedlot-scale measurement using open air techniques (McGinn et al., 2019) to 42% and 27% in backgrounding and finishing diets, respectively (Vyas et al., 2018) Two other experiments testing optimum dose of 3NOP (0 to 200 mg per kg) had mixed results (Vyas et al. 2016a,b). Vyas et al (2016b) fed 3NOP at 0, 50, 75, 100, 150, and 200 mg/kg DM with linear reductions in CH_4 per kg DMI for both high forage and high grain diets and no effect on DMI. Vyas et al. (2016a) observed reductions in CH_4 only when feeding 200 mg/kg DM and subsequent increases in H_2 production. These changes in CH_4 and H_2 immediately ceased when 3NOP was removed from the diet.

Halogen compounds such as bromoform and chloroform have been tested in reducing CH_4, but microbe adaption can occur, removing any long-term reductions. Halogen compounds can have a negative effect on animal liver function, so halogens have not been widely adopted (Machmüller et al. 1998, Finlay et al., 1994, Hegarty 1999).

Water Vapor

Water vapor (H_2O) is considered a GHG and has the ability to trap heat. However, that vapor is immediately released into the rainfall cycle, so water vapor is not considered a major contributor to carbon balance or global warming.

Nitrous Oxide

Nitrous oxide (N_2O) has a greater GWP than CH_4 and ranges from 265 to 298 times that of CO_2. Cattle do not produce N_2O from the rumen, but rather it is produced from the natural degradation of nitrogen in feces and urine. The nitrogen cycle is the process of nitrification and denitrification that occurs naturally. The N cycle is shown in Figure 1 [adapted from Lehnert et al. (2021)]. A large part of the nitrogen cycle is the fixation of nitrogen both in microbes such as those in the roots of legumes, and also the industrial process of removing N_2 from the atmosphere to produce NO_3 based fertilizers. In the process of nitrification and denitrification, N_2O is an intermediate.

Emissions of N_2O are directly related to the crude protein (CP) level of the diet. As dietary protein level surpasses requirement of the animal, more N in the form of ammonia (NH_3) and N_2O is released. This process can take weeks and emissions slow when soil moisture is very low or very high and when soil temperatures are low. Of all anthropogenic emissions from N_2O, 75% are a product of fertilization of agricultural land (Lehnert et al. 2021). The release of N_2O can occur in solid or liquid manure stockpiles. Factors that increase this loss are moisture in above-ground solid manure or the pen surface and exposure to oxygen. Application of manure to cropland also creates a release of N_2O (Dijkstra et al. 2013). Following deposition of urinary N (urea) in pastures or pens, microorganisms in soil transform urinary N into ammonium (NH_4+) and then into NO_3 and finally to N_2, but only after the release of some N_2O. Bacteria in the soil utilize the N contained in the urine and feces and transform those compounds (Urea-N) into CO_2, CH4, NO_3 N_2O and N_2 (Dijkstra et al. 2013).

Another form of N excretion is ammonia which can form fine particulate matter and acidifies ecosystems and can lead to eutrophication of surface waters (Renard et al. 2004). Chai et al. (2014) measured total ammoniacal nitrogen. Cattle produce 18.5 kg ammonia per animal per year on average which equal to 23.5% of annual N intake of beef cattle. Feedlot steers and heifers, cows, and calves contributed 64.2, 21.1, and 10.7% of all NH_3 emissions. Feedlot, barns and pastures contributed 54.4, 0.2, and 8.1% of total ammonia emissions. Manure storage and land application of manure were responsible for 23 and 14% of all ammonia emissions. Cole (2012) in a review discussed ammonia from both N fertilizers and hydrolysis of urinary N. Net losses from pastures range from 10 to 30% of N intake (Asman, 1998; Bussink et al., 1996; Petersen et al., 1998; Hristov et al., 2011). Half of emissions from agriculture comes from N_2O emissions from soils as a result of fertilization (EPA 2011).

Beauchemin et al. (2010) in a life-cycle assessment of an 8-year rotation of beef production in Canada estimated the emissions from CH_4 and N_2O. When accounting for all emissions in the herd the relative contributions to total emissions (CO_2e) were as follows: 1) enteric CH_4 (63% 2) manure CH_4 5% 4) manure N_2O 23% 5) soil N_2O 4% 6) CO_2 from energy consumption (5%). While emissions from animals and manure can be very small (mg per day) their contribution to GWP is large. In pasture-based systems 82% of urinary N is excreted on to pastures. It is estimated that 20 to 30% of urinary N is leached and 2% is emitted as N_2O (Herron et al., 2017). Stackhouse et al. (2011) measured N_2O emissions from Holstein and Angus cattle in whole-body chambers. Manure from small bottle-fed calves (BW = 54 kg) produced 0.66 mg per animal per day and 159 kg calves consuming starter feed produced 11.8 mg per animal per day. Holstein and Angus feedlot steers (340 to 554 kg BW) produced between 15.5 to 19.9 mg per animal per day. When multiplying CH_4 and N_2O emissions by their GWP, on average CH_4 and N_2O produced 83.1 and 16.9% of total emissions (CO_2e) from animals.

Some strategies to decrease NH_3 and N_2O losses are reducing use of calcium ammonium nitrate fertilizers which can have high emission factors. Other fertilizers such as urea have lower nitrogen emission factors. Nitrification and urea inhibitors slow down the nitrification process, and keep N in the soil. Inhibitors can be cost-prohibitive (Herron et al., 2017). Feeding moderate to high levels of DGS can decrease emissions from methane, but increases total emissions due to increased N_2O emissions from over feeding of CP (Hunerberg et al., 2014). Some methods of reducing NH_3 emissions include decreasing dietary N. Another method is to increase dietary energy levels. There are other indicators that increasing urinary volume by increasing dietary mineral content can reduce N_2O emissions (Dijkstra et al. 2013). In theory, dietary synchrony of N and energy could eliminate N excretion. However, physiological mechanisms of urea recycling move more N to the rumen and N excretion continues even when CP and dietary energy are in balance, so dietary synchrony has never been documented in cattle (Cole and Todd, 2008).

Carbon dioxide (CO_2)

Carbon dioxide is released from the oxidation of carbohydrates in the following equation: $C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$. In nature this occurs in the form of oxidation of carbon. In man-made reactions such as fire, this general reaction is considered combustion. This reaction occurs in many different forms and with many different reactants and substrates throughout nature. Carbon dioxide from respiration is not considered a GHG because it is taken in by the natural carbon cycle (photosynthesis and respiration). In theory, carbon taken in as food is in balance with carbon that is released as CO_2 from respiration and carbon that is returned to the soil through manure. This concept will be discussed in depth in the Carbon Balance section.

Todd et al. (2016) measured 7 kg CO_2 per animal per day respired from grazing cows. Winders et al. (2020) in pen chambers measured CO_2 production for growing and finishing calves. In growing diets, they reported 6,831 g per animal per day, 816 g per kg DMI, 6765 g per kg ADG in *ad libitum* fed growing cattle. In finishing cattle they measured 10,723 g per hd per day, 932 g per kg DMI and 6000 g per kg DMI. Gunter and Beck (2018) measured CO_2 production in grazing beef heifers weighing 364 kg. Values ranged from 4921 to 5882 g per animal per day.

A unique consideration must be made when interpreting CO_2 production from ruminants. All mammals take in oxygen and release CO_2. In ruminants, this CO_2 is a combination of respiration by the animal and fermentation of rumen microbes. Barry et al. (1977) measured concentrations of rumen gases through a fistula before, during and after feeding of wethers in a forage (100% grass hay) and finishing (20% grass hay, 80% SFC) diet fed at maintenance. Data from Barry et al. (1977) were further analyzed by Rha (2021). Before feeding, CO_2, CH_4, O_2, and N_2 proportions in rumen gas were 62, 27, 12 and 2%, respectively. After feeding, those values were 29, 12, 49, and 10%, respectively showing an increase in rumen O_2 and N_2. Colvin et al. (1956) measured eructated gases from trachea through a cannula and compared that to the eructated gases from the mouth. Cattle were given 3 treatments 1) Alfalfa hay (5 lb DM), 2) Alfalfa tops (15 lb DM and oat hay 6 lb DM) or 3) Oat hay (5 lb DM). Volume of eructated and aspired gases was highly correlated. Washburn and Brody (1937) simultaneously measured rumen and respiratory gases in Jersey cows. The hand-drawn graphs are presented in Figure 2. Percentages of respired and rumen gases cannot be compared since no N_2 values are reported in both figures. In respired gases, CO_2 and O_2 follow a direct relationship and CH_4 levels are very low (<1%). The divergence in the rate of CO_2 and O_2 in the first 6 h post feeding indicates more CO_2 in respired gases than O_2. Greater CO_2 than O_2 indicates that some respired gas is from the rumen and not respiration and coincides with an increase in rumen CO_2 gas concentration over the same time frame. During this time CO_2 production in respired air is approximately 33 to 43 L per 30 min while O_2 is 28 to 33 L per 30 min over the 5-hour period. This is true in both forage and concentrate diets. Approximating from the graphs by Washburn and Brody, this resulted in 253 and 284 g

CO_2 for forage and concentrate diets per day from fermentation, respectively. However, the total CO_2 produced by cattle, whether from animal or microbial metabolism, is sourced from feed carbon intake.

The rumen is a site of anaerobic fermentation. In some fermentations such as the fermentation of glucose to ethanol, CO_2 is produced. In theory, through the process of eructation, CO_2 could be released that is not from cattle respiration. Kuhlmann et al. (1985) conducted a series of 59 replications with 4 Hereford cannulated calves. To investigate the sources of respired CO_2 the following treatments were administered: 1) full rumen with fistula sealed 2) full rumen with small hole in the cannula or 3) empty rumen with fistula sealed. These 3 treatments were repeated at 1) rest or walking on large treadmill at either 2) 1.4 or 3) 2.2 m/s for 5 minutes. Absorption across the rumen epithelium during rest increased CO_2 production by 3%. Absorption and eructation of CO_2 together increased by 15% at rest when cattle had full rumens. When the rumen was flushed CO_2 increased 21%. Fermentation produces CO_2 and it is added to respired gas by eructation and absorption. Respiratory exchange ratio (CO_2 production/O_2 production) decreased at rest as rumen transitioned from full to open to empty, but this did not occur during exercise. When the rumen was empty, breathing patterns slowed and calves had difficulty maintaining body temperature. The decrease in respiratory rate may have been due to less CO_2 to be expelled from less fermentation but may have also been related to changes in body temperature regulation. Carbon dioxide production is a function of feed intake and is highly variable. In cattle, expired CO_2 originates from both the lungs and CO_2 produced during rumen fermentation.

METHODS OF METHANE MEASUREMENT

Direct measurement of methane emissions in beef production systems over the last 3 to 4 decades has been attempted using many different techniques over different time and spatial scales. Here, in context of the methods used in this analysis, we briefly review and summarize these methods to provide some understanding of the complexity of this measurement. A summary of GHG methods is presented in Table 1.

Respiration Calorimeter

The gold-standard method for measurement of CO_2, CH_4, and O_2 is the full-body or headbox-style indirect calorimeters. Calorimeters use the difference in incoming and outgoing O_2, CO_2, and CH_4 to calculate the energy values of feeds indirectly. After a period of feeding a given feedstuff, energy retained in the animal is the truest measure of dietary energy. The most direct way of measuring retained energy is through serial slaughter. This measurement can be difficult and requires feeding cattle various feeds at different levels of maintenance for varying lengths of time. Lofgreen and Garret (1968) were some of the first scientists to accomplish this work, and with their data developed the initial data set for cattle energy nutrition still in use today. At slaughter, the relative amount of protein, fat, and water in each animal was used to calculate how much energy had been retained over the feeding period. This was based on standard values of energy contained in protein, fat, and water. This process is expensive, labor intensive, and prone to errors, but is the only way to directly measure retained energy

Headbox calorimeters do not measure hindgut fermentation and assumptions must be made of CH_4 production leaving the anus, whereas this would be measured in a full-body system (Birkelo et al., 2004). While the CO_2 and CH_4 values are useful for calorimetry purposes, they can also be used to express hourly, daily, and per unit feed intake gas values in controlled settings. Calorimeters are useful, but are limited to measuring harvested feeds. Many methods have been developed in recent decades to measure GHG in grazing scenarios.

Aerial

In 2016 scientists from Flinders University in Australia flew a plan with quantum scale cascade laser gas analyzers over a 17,000 hd feedlot. In addition, they used ground-based inverse dispersion techniques and eddy covariance to make fine-tuned calculations. Elevated levels of CH_4 and NH_3 were detected 25 and 7 km downwind from the feedlot, respectively. Hacker et al. (2016) used repeated transects to build 3 dimensional plumes. This established the width and depth of the plumes, but the height of the plumes was also shown. Methane plumes were constant from ground level until 150 m of altitude when concentration decreased from 145 ppb to 128 ppb. Ammonia plume air concentrations were higher at lower altitudes (290 ppm at 32 m and 40 ppb at 310 m). They were even able to detect CH_4 emissions from small (20 hd), isolated herds placed in fields for measurement. This experiment helped quantify how these gases travel from large animal feeding operations.

Wind Tunnel

Lockyer and Jarvis (1995) made a portable wind tunnel to measure methane production from grazing sheep. Several experiments were conducted measuring the difference in methane concentration in incoming and outgoing air from the windtunnel. Sheep were in the wind tunnel for 19- 26 hours at a time. Technical difficulties occurred with the sensors and keeping sheep comfortable enough based on the conditions. They measured 7.7 to 18.7 g CH per animal per day. While the windtunnel concept is flexible, it is limited to small ruminants and for animals that can quickly graze the area within the wind tunnel. This confinement also limits their natural grazing patterns.

SF_6 Tracer

The tetrafluoride sulfur (SF_6) tracer method has been the gold standard of measuring CH_4 in grazing scenarios. Before the start of cattle measurement, a bolus of solid SF_6 is measured. The bolus is put in a water bath and weight loss is measured over time. This is typically 500 – 1000 ng per minute. The known loss percent for each bolus is now calculated and the bolus is put into the rumen. Since the boluses are heavy, they stay in the reticulum and are unable to pass through the GI tract. The animal wears a special apparatus that collects air in close vicinity of the nose and deposits the gas in a cannister that hangs from the animal's neck. That air contains both SF_6 and CH_4. The air cannisters are then removed from the animal and taken to a lab and analyzed for CH_4 and SF_6. The SF_6 acts as a tracer because it gives indication of the total volume expelled gas collected. The concentration of SF_6 and CH_4 are compared and the concentration of CH_4 is calculated. (Johnson and Johnson, 1994). This method has compared well to the same cattle consuming similar diets in an indirect respiration calorimeter (Johnson and Johnson, 1994). However, only enteric production is measured. Hindgut fermentation accounts for approximately 3% of CH_4 (Munoz et al., 2012). A diagram of the SF_6 tracer can be found in Figure 3 (McCaughey et al., 1997).

Pen Chamber

Various chambers have been constructed to measure multiple animals at once. Beauchemin et al. (2006a and b) and McGinn et al. (2004) used 4 chambers that each house 2 animals for 3 days at a time. These sensors utilize the Ultramat 5E laser by Siemens Inc. This chamber has been used to test *ad libitum* vs restricted feeding in high forage and high grain diets and effect of sunflower oil, monensin, yeast, and fumaric acid on CH_4 production in growing diets. Winders et al. (2020) used a pen chamber that can house 2 separate pens of animals simultaneously and each side can feed up to 8 animals at a time. Animals are inside for 5 days, then manure measured for 1 day, followed by a 7th day of no animals or manure. Air is continuously sampled from each chamber and ambient air which passes through 2 open path lasers (LI7500 for CO_2 and LI7700 for CH_4). This chamber has been used to evaluate pen-scale GHG emissions in limit fed vs ad libitum, forage diets, and adding corn oil or not to finishing diets (Winders et al. 2020). Stackhouse et al. (2011) used a chamber that measures GHG from 3 animals for 24 hours at a time. Incoming and outgoing air are sampled and uses a TEI 55C Direct Methane Non-Methane Hydrocarbon analyzer (Thermo Environmental Instruments). This chamber was used to evaluate bottle-fed and starter-fed Holstein calves as well as Holstein and Angus steers fed steam-flaked corn-based finishing diets. While these chambers are of varying sizes and use different instruments for measurement, the calculated CH_4 emissions are based on incoming and outgoing air, accounting for total air volume through the system.

GreenFeed

The GreenFeed system is an automated supplement feeder. Through a negative air pressure system, respired air samples are gathered as cattle consume bait supplement similar to a headbox indirect calorimeter. Different supplements can be fed at different levels, different amounts, and different frequencies throughout the day (Gunter et al., 2017a and b). These values give snapshots of CH_4 throughout the day and have been validated by comparing to SF6 and indirect calorimeters (Jonker et al., 2016). Often these systems can be powered with solar technology, making them versatile and able to be used in a variety of locations and environments.

Open Air Measurement Techniques

Over the last 30 years, attempts have been made to develop automated, high throughput data measures of CH_4 from cattle in their natural environment that do not require frequent handling of the animals and also account for the carbon sequestration of the environment. These methods use meteorological data to estimate the carbon flux in and out of a given area using the internal boundary layer. The internal boundary layer (IBL) is the area where the air stream at the measurement height is in equilibrium with the surface that is measured and the vertical flux at measurement height is the same as the vertical flux of the surface. Research described below is summarized in Table 2.

Mass budget (MB) or Integrated horizontal flux (IHF)

The mass budget or balance technique uses the difference in gas concentration at 2 different heights and both up and downwind of the source. Biases can occur without measurement of turbulent flux and atmospheric transport (Gao et al, 2009). The max height is when mean horizonal flux equals zero. In other words, the incoming and outgoing air volumes are equal. Mass balance does not require the source of CH_4 to emit homogenous concentrations of GHG. Flux is assumed to be uniform at any given height.

The best application of IHF are stationary manure storage areas when C_d and u values are uniform. If they are not uniform then u and C must be calculated using multiple (in many cases 5) heights. A modified version of IHF which uses modified mass difference quantifies concentrations and wind speeds at different heights on the perimeter of the studied source. The strength of the CH_4 source does not need to be evenly distributed in this scenario. Gao et al. (2009) describe that time-average product and u and C should be considered in the calculation. This error can cause an overestimate of 5 to 20%.

Harper et al. (1999) first used the technique to measure methane from both cattle in pasture and feedlot setting. It is called integrated horizontal flux because this technique requires sample lines both up and downwind as well as a mast with sampling at multiple heights (0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m). Sample lines for closed-path laser were spaced on all 4 fences to adapt to changing wind directions. The data from the up and downwind samplings is combined with data from vertical profile measured from CH_4 at different heights. Corrections must be made for crosswind variation depending on the distance between the profile mast and the downwind sampling line, contributions to the horizontal flux above the top measurement height and turbulent backflow (Laubach and Kelliher 2004).

Integrated horizontal flux accounts for CH_4 entering and leaving from a small source. No restrictions are considered to the distribution of the source. Emission is the sum of mean horizontal fluxes that accumulate over the source height.

$$Q = (1/x) \sum_{Z1}^{Z2} \quad [u(Cd - Cu)]\Delta z$$

U = windspeed in m/s. C is concentration of gas (g/m^3). Subscripts d and u are downwind and upwind concentrations.

The IHF method has shown to correlate to both simultaneous SF_6 tracer methods and estimates of methane loss based on digestibility and GE loss (Harper et al. 1999).

Flux gradient (FG)

Flux gradient (FG) is calculated using the turbulent (eddy) diffusivity (K; m2/s) and the vertical concentration gradient. Turbulent diffusivity is a function of height, friction velocity, and the stability parameter. The emissions from the upwind area, known as the footprint, are then related to the gas flux. Models are developed to describe the footprint in terms of the distance from the point of measurement. Measurements are taken at 5 heights and differences in concentration between those heights are used to determine the flux. The flux is then divided by the area of the footprint to express gas per unit area. If a known number of animals are in that area, then this can be divided by the stocking density in that area. The difference in the flux gradient from the IHF method is that flux gradient calculates a footprint area instead of depending on upwind and downwind measurements.

Km = ku*z/phi(m)

The von Karmon constant (k) relates size of eddies to heights, friction velocity u*; m/s is calculated using wind statistics from three dimensional sonic anemometer. Z(m) is the height over the surface and phi (m) is a correction for effect of thermal stability on wind profile.

Q in $g\ m^{-2}\ s^{-1}$ is

$Q = ((-kzu^*)/phi \times Sc) \times (\text{change in } C/\text{change in } Z)$

Backward Lagrangian Stochastic Model (BLS)

This method uses a series of lasers on the perimeter of grazed areas. The infrared lasers bounce off mirror (retroreflector) systems and reflect back to the detector and receiver optics. The strength of the return signal is proportionate to the concentration of methane between the laser and retroreflector (Flesch et al. 2004). The accuracy of this method is not dependent on the size or shape of emission source, but uniform emission rate must be assumed in the measured area (Gao et al, 2008). Air particle flow through the system can be analyzed both forward and backward through time. With forward mode air parcels start at the same point and the how gases mix into air parcels downwind is predicted. In backward mode, from a fixed sensor the model calculates where air parcels (25 to 40k) originated from. This normally predicts when air parcels touched the ground. The strength of a gas source from a known location (location of the cattle) is determined from this information (Laubach et al. 2008). The backward Lagrangian stochastic dispersion technique has had the most adoption in scientific studies (Flesch et al. 2004, Flesch et al. 2009, McGinn et al., 2009, McGinn et al., 2014, Flesch et al. 2017). It uses the inverse dispersion and can utilize a single source of emissions and wind information. The WindTrax model (Thunder Beach Scientific, Halifax, NS, Canada) is used in the BLS dispersion model which relates the concentration C_{SIM} within the dispersion to a simulated source $Q_{SIM.}$ The C measured value is divided by the simulated ratio (McGinn et al. 2013).

$Q = C_{measured} /(C/Q)_{SIM}$

BLS also uses a sonic anemometer to determine roughness, u*, L and wind direction. Some limitations include the requirement of area source of emission to be well established or exact location of point sources. Background concentration must be determined. BLS model may not work well at low wind speeds ($u^* < 0.15$ m/s), strong stable or unstable atmospheric conditions ($L < 10$) when wind profile is unrealistic (Flesch et al., 2009).

Gao et al. (2008) compared the BLS and MB over a non-grazed grassland and found the two measures to be in agreement. Laubach et al. (2008) compared FG, MB, and BLS methods and compared them to using the SF_6 tracer method. Cattle locations were not known, but the pasture was split in 8 equally sized paddocks. Days in each paddock were recorded and minimum distance from the measurement point was known based on which paddock was being grazed. When cattle were close to the measurement point overpredictions for MB technique were 39 and 19% for data less than 5 or 22 m from the mast. For the FG technique an overprediction of 64% occurred for data 5 m or less. The BLS technique was similar to MB since data 5 or 22 m from the mast over-predicted emissions by 45%. All 3 techniques MB, FG, and BLS were in agreement when data were greater than 22 m from the mast. McGinn (2013) summarized BLS, IHF, and FG methods. When comparing the suitability of application in various settings, all 3 can be used with some level of success. However, IHF may not be the most suitable for pasture or farm situations but would work well monitoring uniform sources such as a lagoon. BLS is the most flexible for detecting methane from cattle or manure in pen or pasture scenarios.

Todd et al. (2018) used the Windtrax BLS to solve an open path source from each cow. The emissions, after accounting for background flux, were calculated after simulating emissions from 5000 parcels of CH_4 per point source (each cow). The 15 minute average locations of each cow were superimposed on a map. The cows contributing to the downwind flux were then counted. The BLS model was calculated again for area source dispersion, but contributions were assumed to be uniform across the grazed paddock. The values from area and point source were in agreement with values measured from simultaneous GreenFeed CH_4 measurements and IPCC tier 2 emissions based on forage type and intake. While this experiment looked at both point and area source emissions from grazing cows, the eddy covariance (EC) technique was not used, but rather a modified version of the BLS model. McGinn et al. (2009) used a similar technique with cattle in feedlot pens consuming mid-energy diets (60% barley silage with 35% barley grain or DDGS). The BLS model using GPS coordinates to calculate point source emissions was between 14% underestimate and 7% overestimate compared to simultaneous SF_6 tracer values.

Eddy Covariance

The use of eddy covariance (EC) to measure cattle GHG emissions/fluxes developed naturally after the adoption of the other techniques described above. The advantage of EC is that it directly quantifies greenhouse fluxes emitted by the ecosystem while not disturbing animal behavior or plant growthTthe covariance between vertical velocity and the greenhouse gas are used to calculate the emissions as a vertical flux averaged over an area upwind of the sensors. Fluxes are calculated as the products of instantaneous fluctuations from the mean (covariance) of vertical wind speed (w, m s^{-1}) and CH_4 concentration (C; g m^{-3})

$Q = w'C'$

Theproduct of these two measures is averaged over a 30-minute interval. The value of w must be measured from a three-dimensional sonic anemometer. Coordinate rotations are done after measurements have been taken to ensure the mean of w is equal to zero. The footprint of the emission source is dependent on surface roughness, measurement height, windspeed and direction and atmospheric stability (McGinn 2013). Open or closed path lasers can be used to quantify the gas concentration. In a closed path laser, the air is sampled from the same height as the sonic anemometer and an adjustment must be made for the time delay in air flow to the laser compared to instantaneous sonic anemometer data. The closed path system requires more power for a large air pump but is more accurate (Peltola et al. 2012).

When applying EC to a livestock grazing scenario, the footprint is constantly changing based on wind conditions. While the stocking rate of the pasture is well known, the exact stocking rate of the footprint area is not known without accurate animal GPS data. Assumptions are that: 1) flux is constant with height, and 2) upwind area is homogenous. Some discussion in the literature debates the importance of CH_4 source height relative to mast height. Mast height is normally set at 2 or 3 m above ground level. Most EC data are collected assuming all sources and sinks are within the canopy (vegetation) height. Cattle muzzle height is approximately 1 m above canopy height depending on animal size. Coates et al (2017) simulated cattle grazing with artificial methane sources scattered at a height of 0.8 m. Using a Lagrangian stochastic model considering different source heights, emission estimates were computed with 10% error regardless of height. McGinn et al. (2015) looked at both point source, area source, and elevation of area source and their effect on CH_4 production. They found no effect of mast height on GHG production (0 m vs 0.5 m). Distance from the mast affects accuracy in BLS, FG, and MB techniques. Using EC technique, Dumortier et al (2021) used a model by Kljun et al. (2015) and tested if the artificial source was located further from the mast carrying the sensors than the maximum of the footprint function. The drawback of this model is that it assumes all sources are at ground level. In a previous validation of their technique Dumortier et al. (2019) assessed other models that assume source height. Using the Kormann and Meixner (2001) model they could estimate emissions with error of 15% or less.

Baum et al. (2008) used a footprint model by Hsieh et al (2000) when estimating CH_4 from feedlot pens. They estimated that three pens south of the tower contributed 61% of the emissions while the roads, feed bunks and transfer alleys accounted for 21% of the measured flux. Similar methods were used by Bai et al. (2015) and Prajaya and Santos (2016) over large feedlot operations who measured 132 and 141 g CH_4 per animal per day, respectively. The CH_4 flux in these scenarios, like other open-air measurements above, have made the assumptions that flux is relatively constant across the surface. In the last 7 years, an important distinction has been made in these measurements 33arametn using area source and point source. Cattle move while grazing based on biomass availability, and that grazing distribution at any given time is not homogenous (Dumortier et al. 2021). The fetch area is dynamic and moves based on wind direction and changes in size based on surface roughness and wind speed. New developments use animal coordinate data in combination with EC techniques to measure animals as point sources.

For EC to be used accurately, measurements of animal locations must be made relative to the fetch area. The two most relevant studies of using EC on grazing cattle using GPS coordinates are Felber et al. (2015) and Dumortier et al. (2021). Felber et al. (2015) measured CH4 using EC and tracking animal movements with GPS units. Methane production was 423 ± 24 g per animal per day, but a distinction was made between animals that were "near" and "far" from the EC tower. This distinction was made based on the distance of the grazed paddock from the EC tower (cattle rotationally grazed between 6 paddocks). Consideration of "near" cows using GPS location resulted in 423 ± g CH4, while far cows was 282 ± 32 g per animal per day. The PAD method was also used, which relied on stocking density notes

Dumortier (2021) monitored 19 cows and calves and one bull on a pasture over 19 months. EC data in combination with GPS locations were used to estimate animal location within the fetch area. On average, emissions were 220 ± 35 g CH_4 per livestock unit (LU, 454 kg animal) and 80 ± 13 kg CH_4 annually. Cow/calf pair DMI was estimated after accounting for forage height before and after grazing (9.5 kg DMI) (Gourlez de la Motte et al. 2018).Felber et al. (2015) and Dumortier (2021) both used the Kormann and Meixner (2001) footprint model. For Dumortier (2021) flux measurements were expressed as nmol per m^2 per second (F_{CH4}). Since animal data were measured every 5 minutes and animals occupied 6 positions during each 30 min window, GCF x $1/6 \sum i \, \phi i$, which is the stocking density in the footprint. Combining the GPS and individual animal data took on the following form:

Flux per animal = F_{CH4} / (GCF x 1/6 $\sum i\ \varphi i$

The flux per animal (f_{CH4}) was calculated as the slope of the linear regression associated with the relationship of stocking density in the footprint and measured methane flux. For the regression calculation Linear Least Squares regression was used to minimize residues in the vertical axis and assumes no uncertainty in the horizontal axis. To deal with uncertainties in both axes the Reduced Major Axis (RMA) method in Matlab minimizes residues in both the horizonal and the vertical axis. For Felber et al. (2015) average cow emissions were calculated from GPS and flux measurements:

Footprint weight of the herd = n_{cows} x footprint weight of each cow = $n_{cow\ x}$ [1/n $\sum \varphi\ (x_i, y_{i,}]$

Average cow flux = (Flux from EC – flux from soil) / footprint of the herd

This was similar to Dumortier et al. (2021). However, Felber took the mean of x and y coordinates of every animal in 3 minutes because they recorded 5 second GPS positions instead of 5 minute. Felber et al. (2015) calculated an average flux after removing outliers while Dumortier et al. (2021) calculated the regression of the relationship between flux and animals in the footprint. Dumortier et al. (2019) was a validation experiment to ensure the point source method was accurate moving methane cannisters on a truck. This method determined the model calculation captured between 90 and 113% relative to what was released from the cannisters. Coates (2017) conducted a similar experiment using photographic images to determine animal location by back calculating GPS position from pixel coordinates in photos relative to the fetch area. When comparing EC area and point source to laser technique and predicted emissions based on intake there was no advantage in accounting for individual animal positioning. EC area and point source data were highly correlated but under predicted based on intake and the laser technique.

No estimate of animal feed intake or CO_2 from respiration was done by Felber et al. (2015) or Dumortier (2021). Felber et al. (2016) used the same EC data to estimate C balance of the pasture. Net ecosystem exchange (NEE) was calculated for all data and compared to NEE when no cattle were in the footprint. The comparison of these fluxes was 4.6 kg C (16,868 g CO_2) animal^{-1} day^{-1}. In addition, the pasture after subtracting out animal CO_2 was -68 g C m^{-2} meaning the pasture was a carbon sink, likely due to increase in soil carbon.

Gourlez de la Motte et al. (2018) used data from the same herd as Dumortier et al. (2021) but instead measured carbon flux. Calves and heifers were assumed to produce 60 and 40% of emissions from cows, respectively, in the herd. Cow CO_2 emissions were estimated at 3.0 +/- 0.8 (kg C 11 kg CO_2) per cow per day. After accounting for CO_2, C sequestration from continuous grazing over the growing season varied from -123 to 49 g C m^{-2} with an average of -74. Continuous grazing varied from -153 to 77 g C m^{-2} with an average of -88 g C m^{-2}. In both cases grazing pastures was a C sink.

Soil Carbon

Various methods have been used to calculate the carbon balance from a grazed ecosystem. While cattle are consuming carbon in the form of grass, carbon is simultaneously coming into the system via photosynthesis. Stanley et al., (2018) estimated that grain- finished systems produce 6.09 kg CO_2e per kg HCW. Grass finished systems can produce 9.62 kg CO_2e per kg HCW, mostly due to enteric methane production and reduced HCW (280.2 vs 405.8) (Stanley et al., 2018). Soil carbon flux can decrease CO_2e by increasing carbon soil flux by 3.59 Mg per ha. This sequestration is enough to change grass-fed beef production from a source of 9.62 kg^{-1} CW CO_2e to a C sink of 6.65 CO_2e kg^{-1} CW. Teague et al. (2016) theorized that adopting 25, 50, or 100% regenerative adaptive multipaddock (AMP) conservation grazing could change the C status of current livestock and crop production from an emitter of 0.27 Gt C per year to a sink of 0.7 Gt C per year. The AMP method is designed to mimic ancient grazing patterns by large herds of ruminants across the plains. More recent evidence suggests that AMP can retain 13% more soil C and 9% more soil N (Mosier et al., 2021). Gourlez de la Motte et al. (2018) investigated continuous and rotational grazing by a Belgian Blue cow/calf herd on perennial ryegrass and white clover. Carbon flux was calculated in a similar manner as Felber et al. (2016). They found carbon flux to be 74 and 88 g C uptake per m^2 for continuous and rotation al grazing, respectively, over the grazing season after accounting for CO_2 from animal respiration.

Minasny et al. (2017) theorized the practical implications of increasing soil carbon worldwide. Highly managed agricultural soils would be able to achieve the increase in C soil in the top 1 m of soil which would be enough to offset 20 – 35% of all anthropogenic GHG emissions. A major limitation is soil C saturation. Soil C sequestration rates range from 0.22 to 8.0 Mg C per ha per year.

McGinn et al. (2014) used the BLS method to estimate total carbon budget of a grassland over the grazing season. Cattle averaged 189 g CH_4 per animal per day. After assuming 4,200 g of respired CO_2 per day (from indirect calorimetry with similar animals) grassland C balance was calculated. Carbon balance peaked at 2.2 g per m^2 per hour in early July and was negative by August. When stocking at 0.1 animals per ha, the grassland was a sink of 40 kg C per ha per year. At 0.2 animals per ha the pasture was a C source at 0.7 kg C per ha per year. If expressing C from CH_4 on a CO_2e basis, the grassland was always a source of C, between -9 and -338 CO_2e per ha per year for 0.1 and 0.2 animals per acre, respectively.

Carbon Balance

Considering CO_2 from respiration as part of the ecological C balance is an important distinction made in recent studies including Felber et al. (2015), McGinn et al. (2014), Minasny et al (2017), Mosier et al. (2021), and Stanley et al. (2018). Previous literature used IPCC guidelines for considering respiration CO_2 as part of biogenic C. Using this source CO_2 as part of carbon balance is necessary component to include in the carbon balance from beef production. Since carbon (feed) intake is considered part of the biogenic cycle, when conducting open-air C measurements, new questions arise when considering all potential routes of carbon intake. This leads to discussion regarding *in vivo* carbon balance based on previous literature. In the following section, inputs of C will be compared to all outputs of C including CO_2, CH_4, manure, urine, milk, and body retention. Balance of N is also reported due to the high GWP of N_2O emissions.

Ample information exists in scientific literature regarding cattle energy, C and N metabolism. Metabolism studies such as those summarized below form the basis of beef and dairy cattle nutrition using indirect calorimetry to estimate energy balance. The flows of C, N, and energy are complex, and an effort is made to summarize those flows so that nutrient fluxes into and out of the environment are better understood. Below are the relationships used to determine energy fates *in vivo* and calculations of feed energy values (Lofgreen and Garret 1968)

Gross energy - fecal energy = Digestible energy

Digestible energy – urinary energy – methane energy = metabolizable energy

Metabolizable energy – heat production (maintenance energy) = net energy of gain

Net energy of gain = retained energy

Each of these factors can be back-calculated if all others are known. Animals spend multiple days in the headbox as incoming and outgoing gases are sampled and kept in bags. Subsamples of these gases are measured and production of CO_2, O_2, and CH_4 are calculated based on the difference in air concentration. Calorimeters, instead of directly measuring retained energy, use oxygen consumption to estimate heat production. Fecal, urine, and methane energy are all directly measured. Heat production is calculated from O_2, CO_2, and CH_4 production from respired gases as well as nitrogen loss in urine using the Brower equation. Retained energy is then determined by difference since it is the only value in the above equation that is not known.

$HP = (Mcal/d) = 3.866 \times O_2(L) + 1.200 \times CO_2 (L) – 0.518 \times CH_4 (L) – 1.431 N (g)$ (Reynolds et al., 2018). This review summarized the following literature and made estimates of carbon and nitrogen balance: lactating dairy cows: Aguerre et al. (2011), Foth et al. (2015), Judy et al. (2019a,b) and Morris et al. (2021), dry and lactating beef cows: Andreson et al. (2020), Chung et al. (2013), Freetly et al. (2008) and Wiseman et al. (2020), growing steers and bulls consuming low to mid energy diets: Cole et al. (2020), Posada-Ochoa (2016), and Wei et al (2018), finishing steers consuming high energy diets Hales et al. (2012, 2013, 2014, 2017). These are presented in Table 3 and Figure 3. Carbon and N fluxes were calculated from reported DMI and losses in urine, manure, and milk. Carbon balance was calculated assuming OM was 42% C, CO_2 equal to 27.3% C, and CH_4 equal to 86% C. Contributions of milk to C after assuming all milk was 3.5% fat (70% C), 3.2% protein (42% C) and 4% lactose (40% C). Reported milk N values were used to estimate N loss in milk as a proportion of N intake. When N intake was not reported, diet CP% was multiplied by 0.16 to determine N intake (g) from DMI. Flows of C, N, and energy are dynamic based on physiological state, diet, and intake. Methane has a large direct contribution to GWP, but small amounts of C intake are lost as CH_4 (1.5 – 5.2%). Loss of C from CO_2 are variable with intake and flow to milk (20 – 50% of C as CO_2). Greater intakes of N were required in lactating beef and dairy cattle. This decreased N retained since 15 to 29% of N was put to milk production. The most accurate values are those in finishing steer category since reported values are the means of the treatment means from Hales (2011, 2013, 2014, and 2017). Direct measurements of energy, C, and N balance were reported in these studies.

Reported values for gross energy intake (GEI), urinary energy, and fecal energy were used to calculate digestible energy and metabolizable energy (ME). Energy retained in tissue was calculated after subtracting fecal, urinary, milk and heat production. Some retained energy values may seem high. All error in measuring fecal, urinary, milk and heat (for energy) in the other estimates is captured in retained energy, since it is determined by subtracting all other values from intake of C, N, or energy. Beef cows, according to this calculation, retained 33.5% of C which is higher than the other physiological states (-4.4, 3.7, and 12.2 for dairy cow, growing and finishing cattle, respectively). This is due in part to other estimates of C fate in beef cows that may be low. Methane production for beef cows is only 108 g animal^{-1} day^{-1} in the studies summarized. This value can be up to 450 g per cow per day based on some micrometeorological measures of grazing cows (Felber et al., 2015). Using similar diet composition intakes from Chung et al. (2013) average CH_4 production is 117 animal^{-1} day^{-1}. A higher proportion of C loss as CH_4 (450 g) would decrease C retained value of 33.5% to 24%. In addition, some studies used in for the beef cow estimate used lactating cows and others used dry cows which adds to the variation in loss due to milk since some studies would have no milk C contribution. Fecal production of C is also low given that TDN of the diets in the beef cow studies averaged 65.1 which is high compared to some grazing scenarios when TDN is often below 50. Lowering TDN would shift C losses to feces. No estimate of urine loss was reported in these studies in beef cows, which would decrease the C retained, but other studies show low average C loss in urine (2.6 to 5%). Lastly, in the beef cow data, no estimate of C retained in conceptus or calf growth can be estimated since no calf birth weight or weaning weights were recorded in these short-duration studies.

Nitrogen shows some of the opposite relationships as C. N retained is lowest in beef cows (7% of intake) and urine loss is high (67.5%). In dairy cattle GEI and DMI were much greater than the other 3 physiological states. Production of CO_2 and CH_4 is also greater in lactating dairy cows. Many of the values in Table 3 are suspect since they were not directly measured and compounding errors from repeated estimates using other estimates. The values in Table 3 are simply an illustration of nutrient and energy flows in different physiological states.

Life Cycle Assessments

Carbon dioxide is the standard gas which is used to measure GWP. There has been debate in the literature regarding the comparative GWP of CO_2, CH_4, and N_2O. Cain et al (2019) calculated that the conventional definition of CO_2e was based on the theory that all CO_2e produce the same amount of warming. Recent data shows that there is a lag in warming based on whether gases fall under short-lived or long-lived climate pollutants. Single number metrics such as CO_2e overestimate cumulative effects of short-lived climate pollutants. If GWP estimates based on CO_2e were accurate, the current temperature increases would be much greater than what has been observed since the year 1900 (Allen et al., 2018, Cain et al. 2019, Smith et al., 2021). In fact, decreasing CH_4 emissions below current levels would not slow the increase in temperatures, but likely cause a decrease in temperatures. However, given all these data, the metric of GHG measurement is entirely determined by the climate policy. Limiting the increase in global ambient temperatures has been the primary goal because of the belief that increasing global temperatures by 1 or 2°C will cause dramatic, detrimental effects to weather patterns, sea levels, etc. Policies have focused on limiting this warming to 2°C or less (Paris Agreement). Current life-cycle assessments of beef production give CH_4 a global warming potential of 23 – 29x that of CO_2. GWP of 20 years gives CH_4 a value of 84x that of CO_2 and expressed over 100 years it is expressed at 29 (IPCC, 2013) The atmospheric life of CH_4 is 9 to 12 years before it is converted to CO_2. GTP100 gives methane a value of 4 times CO_2 and N_2O is 234 instead of 265 (IPCC, 2013). Assuming cattle populations remain constant then warming effect due to cattle should remain the same and decreasing cattle numbers could even give a cooling effect (Thompson and Rowntree, 2020).

Animals are not the only source of GHG in livestock production. Manure and the burning of fossil fuels are other major contributors to the carbon footprint of beef production. Rotz et al. (2019) developed the Integrated Farm System Model to predict environmental footprints of crop and livestock production based on farm inputs. Incorporation of C into the farm ecosystem was not considered in this model. All inputs required to grow crops for feed production and the inputs for grazed forage growth are considered in the model and therefore no consideration for biogenic or respiration carbon. The beef production system was split into 7 geographical regions across the U.S. A majority of water and CO2e emissions were produced from the cow-calf sector. Without considering beef from Holstein production, the southeast region produced the most GHG per kg HCW (28.9) while the southwest region produced the least (20.2). The greater values in the southeast region were due to greater fertilizer use and precipitation in these regions. When incorporating animal inputs from the dairy industry, this lowered emissions in regions where the dairy industry is prevalent (southwest, Midwest, and northwest). Pelletier et al. (2010) examined upper Midwest beef production using either 1) calves weaned directly to feedlots 2) weaned to out-of-state wheat pastures for backgrounding before finishing, or 3) finished on pasture and hay. Feed production was responsible for 71% of land use, and 32.9% of GHG emissions. An attempt was made to determine returns of industrial, edible food, and chemical energy from the three systems The amount of human-edible food energy produced relative to the amount of industrial inputs, human-edible animal feed consumed, and gross chemical energy consumed by cattle. Industrial energy returned 5.2, 4.4, and 4.1% of inputs for feedlot, backgrounding/feedlot and pasture-based systems. Human edible energy returned 4.2, 5.9, and 69.1%, respectively. This was much higher in the pasture-based system since none of the feed on pasture would be considered edible by humans. For gross energy, net returns were 2.0, 1.8, and 1.6%, respectively.

Beauchemin et al. (2010) conducted a life cycle assessment of beef cattle production in Canada over an 8-year cycle. A simulated farm was created in which all farm inputs were considered. Outputs of GHG from this farm were considered as well as output production of feed for cattle and the beef from the cattle themselves. The model accounted for all emissions from cattle, stored manure and manure application. Emissions from this cycle expressed as CO_2e were 63% for enteric CH_4, 5% for manure CH_4, 23% for manure N_2O, 4% from soil N_2O, and 5% from CO_2 from energy combustion. Per kg HCW produced this was 21.73 kg CO2e. Segments of the production system had the following contribution 61% cow/calf herd, 19% from breeding stock, 8% from backgrounding and 12% from finishing.

Basarab et al. (2012) raised calves from a single herd and allocated to 4 treatments 1) calf-fed no implant 2) calf-fed with implant 3) yearling-fed no implant, 4) yearling fed-implant. Calf-feds were put on feed to be finished immediately after weaning and yearlings were backgrounded for 312 days before entering the feedlot. Emissions from cropping, manure, and enteric methane were modeled based off on-farm inputs. Emissions of CO_2e per kg HCW were 21.1, 19.9 22.5 and 21.2 respectively. Including cow and bull herd, total land use was 318.6 318.7, 403.4, and 407.3 ha to produce 56 calves per treatment. Yearling-fed systems required more acres for grassland, but those acres were able to sequester more carbon. After adjusting CO_2e for sequestered carbon, emissions per kg HCW were reduced 10.9% for both calf-fed systems (18.8 and 17.7 kg CO2e) 161 and 15.6% for yearling fed systems (18.9 and 17.9 kg CO_2e per HCW for non-implanted and implanted, respectively).

Stackhouse-Lawson et al. (2012) conducted a life cycle assessment of the California beef production system. Data from Stackhouse et al. (2011) was used in part to estimate GHG emissions both with and without beef production from Holsteins. This assessment was considered both with and without a stocker phase, and assuming calves are grown to the same end BW (571 kg) then with adjusted days on feed. Total carcass weight included both cull cow and finished steers and heifers. This estimate was adjusted to include biogenic CO_2 that is part of the natural carbon cycle. Biogenic CO_2 decreased the CO_2 footprint from 22.6 to 17.7 kg CO_2 per kg HCW. Weaning calves directly into the feedlot with no backgrounding phase decreased footprint to 15.4 and 21.2 with and without biogenic CO_2e.

Several models have been developed to calculate whole-farm GHG emissions from input data. Beauchemin et al. (2011) used the HOLOS model which was a whole-farm model based on IPCC methodology to estimate emissions from major contributors of CH_4, N_2O, and CO_2, in Canada. Various methods of improving C footprint were modeled including dietary (supplementation of fats, distillers grains, improved forage quality) and reproductive (increasing longevity of breeding stock and reproductive performance). With no improvements, 22 kg CO_2e were produced per kg HCW. 80% of emission originated from the cow/calf sector and 20% from feedlot sector. Improvements in the cow/calf herd could decrease GHG intensity from 8 to 17%. Combining strategies in the feedlot sector could decrease GHG emissions by 3-4% and 20% if applied in all sectors.

Other models include the Cool Farm Tool (Hillier et al. 2011) which was designed for any farmer to use to make economic and production decisions based on both the financial and environmental impacts. Standard calculations for all on-farm inputs for crops and livestock were developed. Models not based on North American beef production include Cederberg et al. (2009 and 2011) estimating the carbon footprint of Brazilian beef production and Casey and Holden (2005) in Ireland.

Desjardines et al. (2012) emphasized the consideration of co-products when calculating the C footprint. While most models focus on HCW, untrimmed primal cuts, fat, and bone, hide and offal, while not always put in the food system, are still useable parts of the beef animal. The carbon footprints of primal cuts, hide, offal, fat, and bones were 19.6, 12.3, 7, and 2 kg CO_2e per kg of product. This provides a more complete picture of carbon footprint and brings that carbon into the beef production system and not given to the packing or rendering plant sectors. These are under reported values that need consideration.

Capper et al. (2011) compared the carbon footprint of beef production in 1977 and 2007. Since 1977 U.S. beef production system has reduced total animals in the population by 31%, including slaughtering 23% less animals. Manure, CH_4, N_2O and total carbon footprint have decreased 19, 19, 11, and 16% respectively. Water and land use have also decreased 12 and 33%. In this time period, total beef production has increased from 10.6 billion kg to 11.9 kg (12% increase).

Future improvements in the beef system were analyzed by White et al. (2015). The predicted reductions in carbon footprint were modeled from reproductive, genetic, and nutritional improvements in the cow/calf herd. These improvements included NUT – optimizing nutrition requirements, EPDAI – sire selection through AI, EPD-B – sire selection with on-farm bulls, TWN – increasing twinning rate, EW- early weaning, CW- decrease calving window, EPD-CW – selecting bulls by EPD and reducing calving window. These increased HCW -0.6%, 10.4, 14.1, 51.7, 11.1, 1.9, and 16.7% respectively. The subsequent decrease in GHG emissions were 1.5, 11.1, 11.3, 9.2, 8.5, 3.2, and 13.4%, respectively. While TWN greatly increased HCW per cow, increased feed and land needs did not offset GHG in the same manner.

Another assessment by White and Capper (2013) modeled improving average daily gain or final weight by 15% and the subsequent effect on environmental impact and resource use. To produce the same amount of beef, increasing ADG decreased population (0%), total CH4 emissions (12.8%), N_2O emissions (1.7%), total CO_2e (11.7%) land use (3.1%) and total water use increased 29% due to greater feed needs. Increasing FW decreased population (10.5%), total CH_4 emissions (16.0%) , N_2O emissions (9.2%), total CO_2e (14.7%) land use (9.2%) and total water use (15%).

Beef Production Systems

Production performance in each segment of the beef industry can affect the performance in the other segments. Research has compared different cow systems and their effect on cow performance. Perry et al. (1974) fed cows on 1) bluegrass pasture and wintered with corn residue and hay, 2) bluegrass pasture, summer annual pasture, perennial pasture, and cornstalks and supplement or 3) dry lot cows fed corn silage and supplement. Cow feed costs per year were $40.42, 82.16, and 100.78 per cow per year for treatment 1, 2, and 3 respectively.

Burson et al. (2017) raised cows on pasture (PAS), sandhills calving (SH) or in a confinement (CONF) system. The SH system moved cows that had not calved to a fresh area prior to calving. Calves in the CONF and SH system had lower BW and ADG at 40, 80, 120 days of age and at weaning. Anderson et al. (2013) fed cows in confinement either 15 lb alfalfa/grass hay and and 35 lb silage (CON), 40 lb orn silage and 15 lb alfalfa/grass hay (SUPER) or 40 lb silage 6 lb wheat straw and 3 to 5 lb protein supplement (RES). From birth to weaning SUPER calves had 5% greater ADG (no statistics were reported) than CON or RES calves. Feed costs per cow were $99.96, 105.91, and 105.91 for CON, SUPER, and RES.

Additional research has been conducted with different cow-calf production systems and subsequent performance of those calves in the stocker and feedlot. Cole et. Al. (2017) raised cows in an intensive (INT) system or extensive (EXT) system. Cows in the INT system were fed prairie hay and had access to wheat pasture for 4 h daily. Calves always had access to wheat pasture. Cows in the EXT system grazed native rangeland at lower stocking rate than INT and were given oilseed meal supplement during winter. Calves from the INT system had greater BW during winter, spring, and early and late summer grazing seasons. This trend continued in the finishing phase. Intensive calves had greater initial (371 vs 334 kg) and final BW (668 vs 635 kg) and ADG (1.9 vs 1.7 kg) during the feedlot phase.

Warner et al. (2014) raised cows in a drylot system in both eastern and western Nebraska. Cows were either weaned at 90 or 205 days of age. A location x treatment interaction was observed. Western Nebraska early-weaned cows gained body condition from pre-breeding to weaning. Calf ADG also showed an interaction between early and normal weaning with location. Eastern NE normal weaned calves had greater BW and ADG than early weaned, but no difference was observed in the western NE herd.

In a continuation of the experiment of Warner et al. (2014), cows with summer born calves were either fed in a feedlot or kept on corn residue from November to April for 3 years. Cows on corn residue at both locations lost body condition and confinement cows gained body condition. In addition, calves in the feedlot had greater ADG and weaning weight. Revenue from calf sales was greater in drylot cows because of greater calf weight. The cows that grazed corn residue had greatest net return due to lower feed costs (Gardine et al., 2019).

Carlson (2021) compared conventional (CONV) Midwest beef production to a no pasture system (ALT). The CONV system cows calved in April/May and graze bromegrass pasture from April to October at weaning. Cows then grazed corn residue until next calving. The ALT cows were fed in a drylot from March to October, calved in July/August before grazing cover crops. After weaning in mid-January, cows then grazed corn residue until going back into the feedlot. Over 2 years of the study ALT calves were 45 kg lighter when weaned at same days of age, and showed compensatory gain through the growing period. Cows from the TRAD treatment had greater gain in finishing period and reached 0.5 inch backfat 35 days sooner. Net return from calf revenue as well as cow/calf, growing, and finishing phase net returns were lower in the ALT system.

Water Intake and Usage in Beef Production

Water is the most important nutrient. Becket and Oljten (1993) estimated total water usage at 3,682 L per kg of boneless meat. To produce all beef annually in the U.S., 25.1 trillion L were needed to produce 6.9 billion kg of boneless beef. Of that 25.1 trillion L, 3.0% was directly consumed by cattle, 51.8% for growing harvested feeds, and 44.8% for irrigated pasture, and 0.3% for carcass processing. Some estimates show usage to be as high as 13,000 L per kg of edible beef when considering all types of water (Gleason and White 2019). Water is categorized into 3 types: 1) Blue water is surface and ground water 2) green water is rainwater and 3) gray water is freshwater needed to dilute pollutants. Each of these is considered in the literature when calculating total water footprint. In beef production, the vast majority is green water for crop and pasture growth (Mekonnen and Hoestra 2012).

Arias and Mader (2010) summarized data from 7 studies in shaded and unshaded pens. Separate models were developed for summer and winter months. Climate data variables were used to predict water intake. The best predictors of water intake were minimum and maximum temperature and temperature humidity index (THI). Solar radiation and DMI had smaller influences on water intake.

Wagner and Engle (2021) summarized estimated water intake for cattle varying in physiological state and age based on temperature. For finishing cattle (BW = 544 kg) these values vary from 11.84 L per day 4.4°C to 87.1 L per day at 32.2°C. These are based on estimated intakes of 3.09 to 7.34 L per kg DMI when ambient temperatures rise from 4.4 to 32.2°C. In general WI relative the body weight increases quadratically until a max of 500 kg BW before decreasing quadratically. Capper (2012) showed grass-finished production resulted in a 300% increase in water usage per kg beef produced. In addition, total water use in the beef industry from 1977 to 2007 decreased 12% while beef production increased 12%.

Mekonnen et al. (2019) modeled improvements in meat and milk produced per unit of water used (water productivity WP) in the U.S. from 1960 to 2016. All sectors of production (egg, meat, and milk) had improved WP from 1960 to 2016. Beef WP (kg protein m^{-3} water) increased from 0.028 to 0.055 from 1960 to 2016. Causes of improvements WP were increased livestock productivity, feed conversion and crop yields which decreased water needed for feed inputs. The replacement of soybean meal and corn by DG increased WP of poultry, beef, pork and milk by 5, 6, 13, and 21%, respectively.

SUMMARY

Agriculture and specifically livestock production are a contributor of GHG, but net carbon balance from beef systems after accounting for ecosystem uptake of atmospheric carbon is not well understood. Extensive measures and models of GHG production from beef cattle have been published. Methods of measuring methane have evolved over time. Controlled chambers have been used to provide accurate estimates of enteric fermentation, and SF_6 tracer method can measure cattle in grazing environments for short periods of time. New methods use rapid laser techniques to quantify emissions continuously in open-air systems. These new measures are complex and often require filtering of data when cattle are not in proximity of the laser. An encouraging aspect to these new measures is the simultaneous measurement of carbon sequestration and soil carbon flux. Certain scenarios have shown that the sequestration of carbon outweighs GHG production, making beef production a carbon sink instead of carbon source to the environment. Keeping in mind these new techniques, a better understanding of individual animal carbon flux is needed. The flux of C, N, and energy are different based on the physiological state, intake, and diet composition of the animal. New methods can minimize GHG production and maximize carbon sequestration using grazing management. However, the adoption of different production systems must be informed by previous research measuring beef production per cow and calf performance post weaning. The feed availability and environment can have a large impact on cow and calf performance both before and after weaning. Future research is needed to understand animal emissions from birth to slaughter and how management practices and animal performance affect emissions per unit of edible beef.

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TABLES AND FIGURES

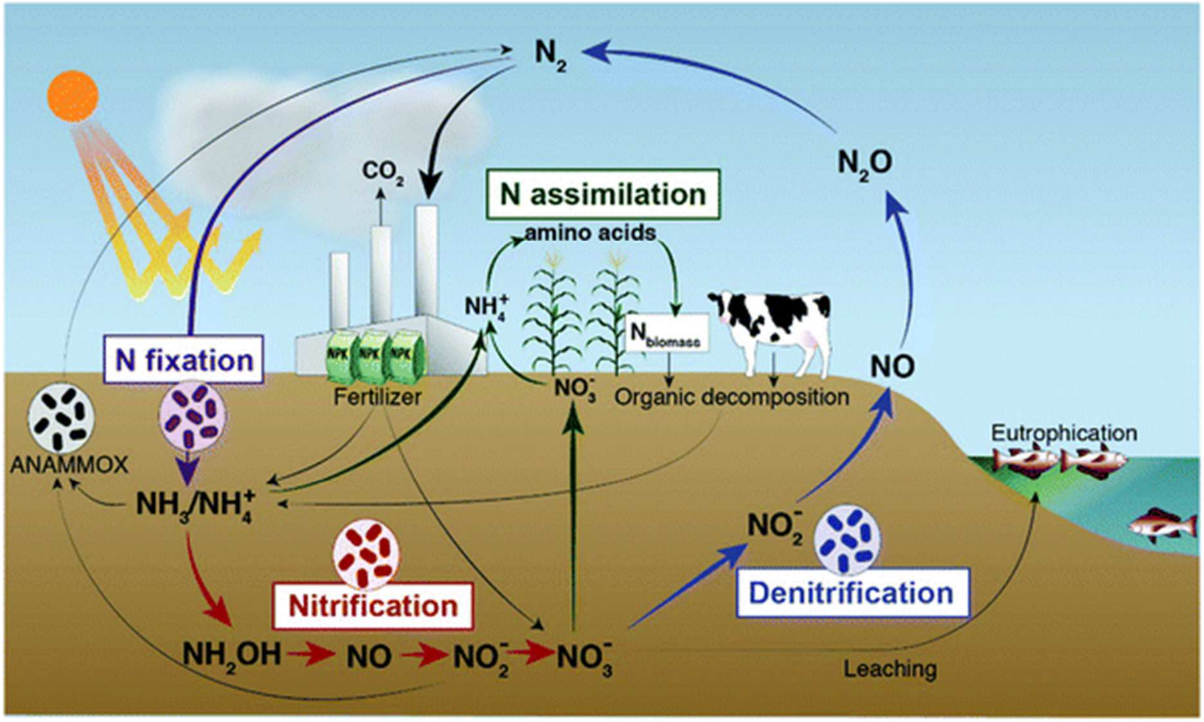


Figure 1.1. The Nitrogen Cycle. Nitrogen cycle in agricultural systems. Adapted from Lehnert, N. B. W. Musselman, and L. C. Seefeldt. 2021. Grand challenges in the nitrogen cycle. Chemical Society Reviews.

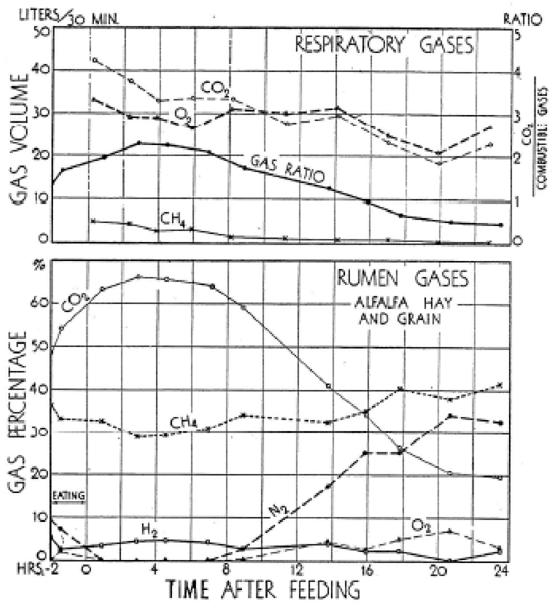


Fig. 4. Same as in Fig. 3, but on a ration of alfalfa hay and grain.

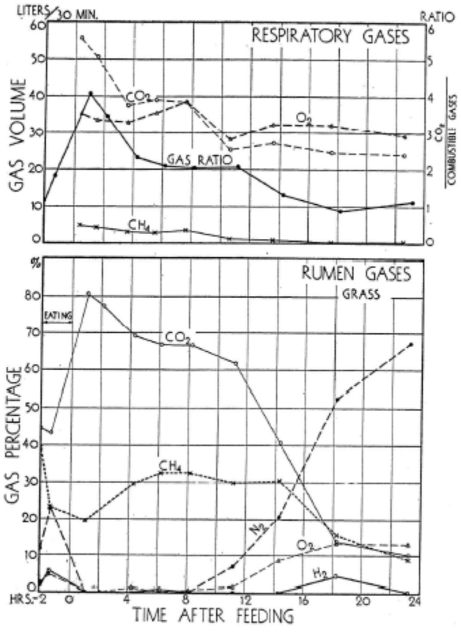


Fig. 5. Same as in Fig. 3, but on a grass diet.

Figure 1.2. Rumen and Lung Gas Production. In the top section, production of respiratory gas volume of CO_2, CH_4, and O_2 after feeding either alfalfa hay/grain mixture or grass hay. Rumen gas proportion of H_2, O_2, CO_2, and N_2 are shown in the bottom sections. Divergent levels of CO_2 and O_2 production in the first 5 hours post feeding in respired gases in combination with large surges in CO_2 in rumen gases indicate that CO_2 from rumen fermentation shows up in expired gases. Original copies taken from Washburn and Brody 1937.

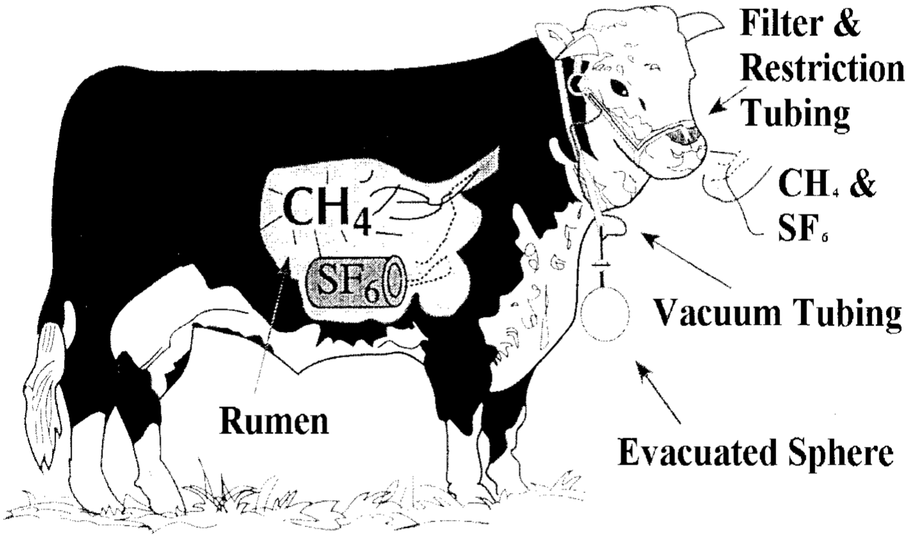
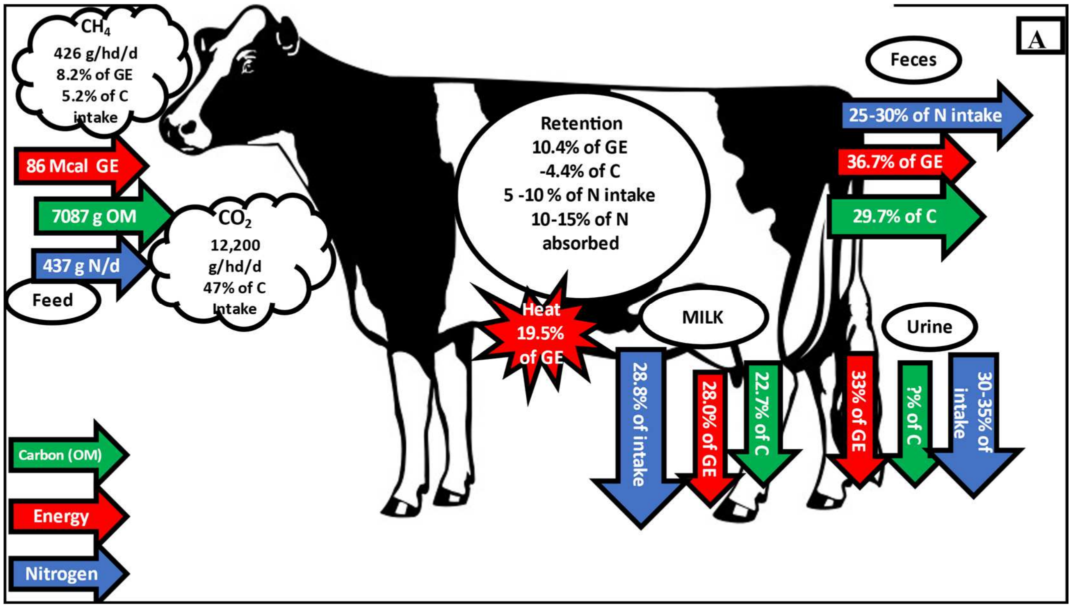
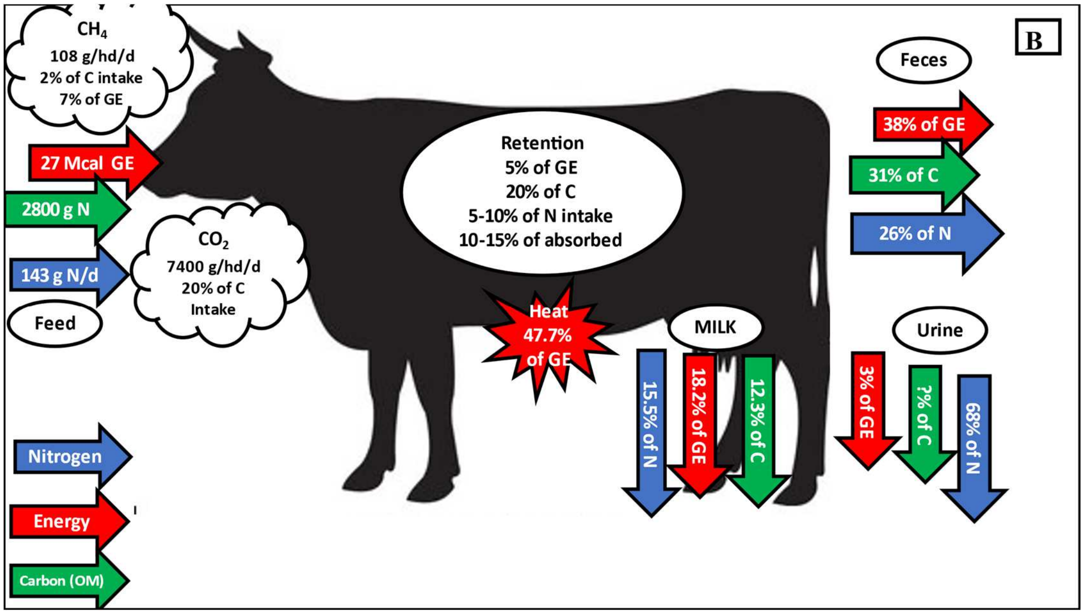


Figure 1.3. Diagram of the SF_6 tracer technique from McCaughey et al., 1997


A
CH$_4$
426 g/hd/d
8.2% of GE
5.2% of C
intake
86 Mcal GE
7087 g OM
437 g N/d
Feed
CO$_2$
12,200
g/hd/d
47% of C
Intake
Retention
10.4% of GE
-4.4% of C
5 -10 % of N intake
10-15% of N
absorbed
Heat
19.5%
of GE
MILK
28.8% of intake
28.0% of GE
22.7% of C
Feces
25-30% of N intake
36.7% of GE
29.7% of C
Urine
33% of GE
?% of C
30-35% of intake
Carbon (OM)
Energy
Nitrogen


B
CH$_4$
108 g/hd/d
2% of C intake
7% of GE
27 Mcal GE
2800 g N
143 g N/d
Feed
CO$_2$
7400 g/hd/d
20% of C
Intake
Retention
5% of GE
20% of C
5-10% of N intake
10-15% of absorbed
Heat
47.7%
of GE
MILK
15.5% of N
18.2% of GE
12.3% of C
Feces
38% of GE
31% of C
26% of N
Urine
3% of GE
?% of C
68% of N
Nitrogen
Energy
Carbon (OM)

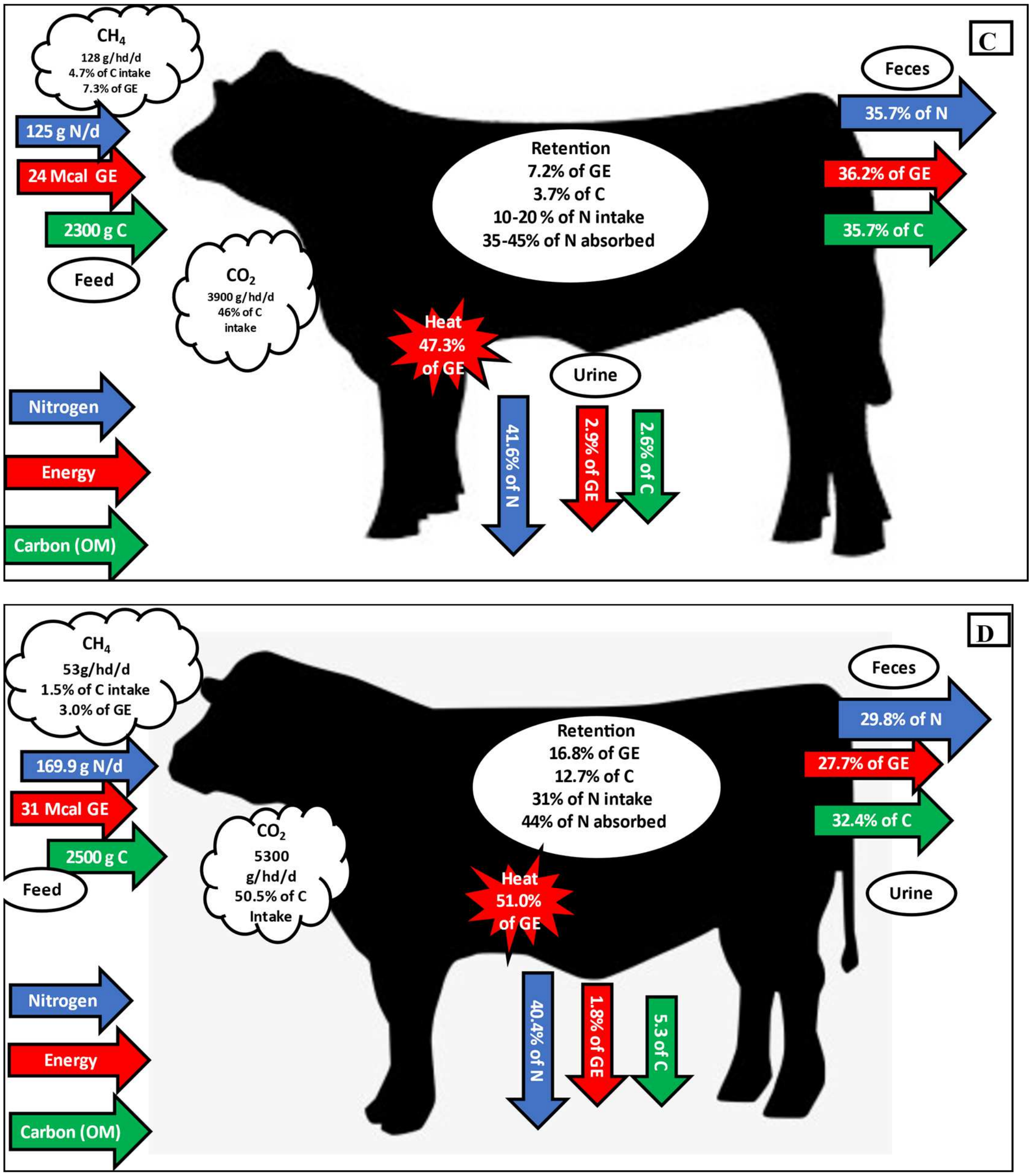


Figure 1.4. Carbon, Nitrogen, and Energy Balance in Ruminants. The fluxes of carbon, nitrogen (N), and energy in varying physiological states: dairy cow (A), beef cow (B), growing steer (C), and finishing steer (D). Data come from the following: lactating dairy cows: Aguerre et al. (2011), Foth et al. (2015), Judy et al. (2019a,b) and Morris et al. (2021), dry and lactating beef cows: Andreson et al. (2020), Chung et al. (2013), Freetly et al. (2008) and Wiseman et al. (2020), growing steers and bulls consuming low to mid

energy diets: Cole et al. (2020), Poisda-Ochoa (2016), and Wei et al (2018), finishing steers consuming high energy diets Hales et al. (2011, 2013, 2014, 2017). Data summarized in Table 1.3.

Table 1. Summary of chamber and tracer methane measurements

Method	Instrument	Description	Diet	Animal Type	Animal number	Animal weight,	Mean CH4, g/hd/d
Lockyer and Jarvis, 1995	Gas Chromatograph	Portable wind tunnel	Perennial ryegrass	Sheep	5	44.5	14
Respiration Calorimeter							
Ramirez-Restripo et al., 2016	Gas Chromatograph	Cattle repeatedly measured over 1 yr period	Ryegrass 1.3x maintenance	Dairy Heifer	10	92	68
Ramirez-Restripo et al., 2016	Gas Chromatograph	Cattle repeatedly measured over 1 yr period	Ryegrass	Dairy Cow	9	508	137
Cole, et al., 2020	Gas Chromatograph	Protein supplementation with cottonseed meal or alfalfa hay	Low and medium quality hay	Steers	8	212	180
Hales et al., 2012	Gas Chromatograph	Evaluation of WDGS energy value relative to DRC and SFC	SFC or DRC with 0% or 30% WDGS	Jersey Steers	8	252	37
Hales et al., 2014	Gas Chromatograph	Evaluation of increasing WDGS level in SFC based diets	SFC based diets with 0, 15, 30, or 45% WDGS	Steers	8	397	45
Nkrumah et al., 2006	Model 880A Infrared Analyzer	Evaluation of cattle with low or high RFI	DRC (yr1) or Barley (yr2) based finishing diets	steers	27	495	92
Esterman et al., 2002	Binos Infrared laser	Cows and calves in chambers- comparing breeds and calf age	50% Grass silage, 35% grass hay, 15% barley straw	Cow/calf pairs	32	525	291
Pen Chamber							
Beachemin et al., 2006	Ultramat 5E, Siemens Inc	Ad libitum or restricted feding	High forage or High grain	Heifers	8	379	142
Stackhouse et al., 2011	TEI 55C Direct CH_4 analyzer	Bottle fed calves, starter feed calves, finishing steers	Starter feed up to high concentrate diet	Beef and dairy steers	52	442	86
Winders et al., 2020	LiCOR 7500 and 7700	Pen chamber with 8 hd per pen	Finishing diet with or without 3% corn oil	Steers	160	370	124
McGinn, et al.,	Utlramat 5E, Siemens Inc	2 animal "pen" Sunflower oil vs monensin vs yeast vs fumaric acid	75% barley silage, 19% Steam rolled barley, 1.5% Canola meal	Holstein steers	16	311.6	155
SF_6 Tracer							
McCaughey 1999	Gas Chromatograph	Cows grazing 2 types of pastures	Grass hay or Alfalfa/Grass hay mix	Lactating beef cows	16	516	259
Johnson et al., 1994	Gas Chromatograph	First study with SF6	Variety of diets - forage and grain-based	Steers and heifers			210
McCaughey et al., 1997	Gas Chromatograph	Rotational and continous grazing with 1.1 steers or 2.2 steers per ha	Brome, wildrye, quackgrass	Steers	16	356	196
Boadi et al., 2002	Gas Chromatograph	Control + 2, 4, or 6 kg/d barley supplementation	Alfalfa-meadow bromegrass	Steers	8	344	230
Ramirez-Restripo et al., 2016	Gas Chromatograph	Cattle repeatedly measured over 1 yr period	Ryegrass	Brahman heifer	10	92	59
Ramirez-Restripo et al., 2016	Gas Chromatograph	Cattle repeatedly measured over 1 yr period	Ryegrass	Brahman Cow	9	508	149
McGinn et al., 2009	Gas Chromatograph	Dispersion in feedlot pens	60% barley silage, 5% supplement, 35% barley or DDGS	Steer	60	330	192
GreenFeed							
Todd et al., 2018	Nondispersive infrared laser	Lactating cows grazed dormant range in Feb with access to Greenfeed	Big bluestem	Beef cows and calves	50	545	334
Cole et al., 2020	Nondispersive infrared laser	Protein supplementation with cottonseed meal or alfalfa hay	Low and medium quality hay	Steers	8	212	180
Manafiazar et al., 2016	Nondispersive infrared laser	Low and High RFI steers	Barley silage	Steers	98	390	212
Hammond et al., 2015	Nondispersive infrared laser	Greenfeed or SF_6 with heifers fed in calate gate bunks	Ryegrass, clover, or flowers	Dairy heifers	20	295	190
Alemu et al., 2017	Nondispersive infrared laser	Testing repeatability of CH_4 from Greenfeed	90% barley silage, 9.4% steam rolled barley, 0.6% Supplement	Beef Heifers	28	344	202

Table 2. Summary of open-air methane measurements

Eddy covariance - Point Source dispersion	Instrument	Description	Diet	Animal Type	Animal number	Animal weight,	Mean CH4, g/hd/d
Dumortier et al., 2021	Picarro closed path laser	CH_4 flux of cows and calves in grazing scenario	66% grasses, 16% legumes, 18% other species	Cows and calves	19	700-750	
Felber et al., 2015	Los Gatos closed path laser	GPS data every 5 s Specify between "close" and "far" animals	85% grass 15% clover mix	Dairy cows	20		424
Eddy covariance - Area Source dispersion							
Tomkins, et al., 2015	Gasfinder 2.0, Boreal Inc	Testing area source dispersion in grazing cattle	Grazing sabi grass, Sirato grass, Stylosanthes, blue pea	Beef steers	48	319	191.2
Bai et al., 2015	Gasfinder 2.0, Boreal Inc	CH4 flux over a commercial feedlot	Barley based finishing diet	18k hd feedlot	17500	396	132
Prajapati and Santos, 2016	Picarro closed path laser	CH4 flux over a commercial feedlot	No diet data	58k hd feedlot	58000		141
Mass Balance - Integrated Horizontal Flux							
Laubach et al., 2008	Ion gas chromatograph	Comparing FG, MB and BLS techniques to SF6 tracer	Ryegrass pasture rotationally grazed in 8 sections	Steers	29	325	198
Laubach and Kelliher, 2005	Gasfinder MC, Boreal Inc	Comparing MB and BLS	No diet data	Dairy Cows	556	520	343
Harper, et al., 1999	Series 225 Gas analyser	Mass balance technique in pens and grazing scenarios	oats and 80% Lucerne	bred heifers	435	436	142
Flux gradient							
Laubach et al., 2008	Ion gas chromatograph	Comparing FG, MB and BLS techniques to SF6 tracer	Ryegrass pasture rotationally grazed in 8 sections	Steers	29	325	264
Backward Lagrangian stochastic modle (BLS) Area Source							
Laubach et al., 2008	Gasfinder MC, Boreal Inc	Comparing FG, MB and BLS techniques to SF6 tracer	Ryegrass pasture rotationally grazed in 8 sections	Steers	29	325	234
Laubach and Kelliher 2005	Gasfinder MC, Boreal Inc	Comparing MB and BLS	No diet data	Dairy Cows	556	520	402
McGinn et al. 2014	Gas Finder, Boreal Inc	Heifers grazing	Wheat grass, Russian wildrye, spear grass, forbes	Angus heifers	40	436	189
Flesch, et al., 2017	Gasfinder 2.0, Boreal Inc	Different number of lasers arranged to cover paddocks	60 -77% barley silage, 17% clover silage or baley straw	Bred heifers or cows	20	452	296
Flesch, et al., 2017	Gasfinder 2.0, Boreal Inc	Different number of lasers arranged to cover paddocks	Swath grazing triticale or corn	Bred heifers or cows	20	462	285
McGinn, et al., 2009	Gasfinder 2.0, Boreal Inc	Dispersion in feedlot pens, lasers on pen perimeters	60% barley silage, 5% supplement, 35% barley or DDGS	Steer	60	381	185
Backward Lagrangian stochastic modle (BLS) Point Source							
McGinn, et al., 2009	Gasfinder 2.0, Boreal Inc	Dispersion in feedlot pens, lasers on pen perimeters	60% barley silage, 5% supplement, 35% barley or DDGS	Steer	60	381	185
Todd et al., 2018	Gasfinder 2.0, Boreal Inc	Comparing GreenFeed, point source, area source	Gestating cows Dormant native range, Point Source	Beef cows and calves	50	545	370
Todd et al., 2018	Gasfinder 2.0, Boreal Inc	Comparing GreenFeed, point source, area source	Lactating cows July tallgrass prarie, Point Source	Beef cows and calves	50	545	537.5
Todd et al., 2018	Gasfinder 2.0, Boreal Inc	Comparing GreenFeed, point source, area source	Gestating cows Dormant native range, Area Source	Beef cows and calves	50	545	380
Todd et al., 2018	Gasfinder 2.0, Boreal Inc	Comparing GreenFeed, point source, area source	Lactating cows July tallgrass prarie, Area Source	Beef cows and calves	50	545	500

Table 1.3. The flux of carbon, nitrogen, and energy from cattle differing in physiological state.

	Dairy Cow[1]	Beef Cow[2]	Growing Steer[3]	Finishing Steer[4]
DMI, kg	19.74	6.15	5.98	6.48
TDN, %	60.29	64.55	62.42	72.32
CP, %	18.48	15.65	11.01	16.32
Energy				
Gross Energy, Mcal/d	86.4	27.4	24.0	31.2
Fecal Energy, % GE	36.7	38.2	36.2	27.7
Digestible Energy, % of GE	63.3	61.8	63.8	73.2
Urinary Energy, % of GE	3.3	2.6	2.9	1.8
Metabolizable Energy, % of GE	59.0	53.0	52.9	75.3
Heat production, % of GE	19.5	47.7	47.3	51.0
Energy retained, % of GE		4.7		
Energy retained in milk, % of GE	28.0	18.2		
[5]Energy retained in tissue, % of GE	10.4		7.2	16.8
Carbon/OM				
[6]Intake, g/d	7086.6	2854.3	2329.3	2518.0
Digested, % of intake	70.4	65.1	63.9	70.9
[5]Retained, % of intake	-4.4	33.5	3.7	12.2
Urine, % of intake			2.6	5.3
Feces, % of intake	29.7	30.9	42.3	32.4
CO_2				
g $animal^{-1}$ day^{-1}	12183.7	7383.3	3928.5	5328.9
[7]% of C intake	46.9	20.1	46.0	50.5
CH_4				
g $animal^{-1}$ day^{-1}	425.9	108.3	127.5	53.0
[8]% of C intake	5.2	3.3	4.7	1.5
% of GE	4.6	5.3	7.0	3.0
[9]C recover in milk, % of intake	22.7	12.3		
Nitrogen				
Intake, g/d	437.1	143.1	125.7	169.9
N digested, % of intake	69.8	74.4	36.3	70.2
[5]N retained, % of intake	8.4	7.0	19.6	30.5
N retained, % of absorbed	12.0	11.7	39.5	44.0
Excretion, % of intake				

Urine, % of intake	32.7	67.5	41.6	40.4
Feces, % of intake	30.2	25.6	35.7	29.8
N recover in milk, % of intake	28.8	15.5		
Studies	6	5	4	4
Treatment means	17	23	17	16

[1] Aguerre et al. (2011), Foth et al. (2015), Judy et al. (2019a,b) and Morris et al. (2021)

[2] Andreson et al. (2020), Chung et al. (2013), Freetly et al. (2008) and Wiseman et al. (2020)

[3] Cole et al. (2020), Poisda-Ochoa (2016), and Wei et al (2018),

[4] Hales et al. (2011, 2013, 2014, 2017)

[5] Calculated from the difference of

[6] Calculated assuming all organic matter intake is 42% carbon, on average

[7] Assuming CO_2 is 27.3% carbon based on molecular weight

[8] Assuming CH_4 is 86% carbon based on molecular weight

[9] Assuming all milk was 3.5% fat (70% C), 3.2% protein (42% C) and 4% lactose (40% C)

Evaluation of methane and CO_2 emissions and carbon sequestration requirement of growing and finishing cattle raised in conventional or partial confinement-based herds

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ABSTRACT

Changes in land availability have made cow-calf production in confinement more appealing both from a management and resource perspectives. A partial confinement system was evaluated to determine differences in greenhouse gas (GHG) emission compared to the conventional summer grazing system. One hundred and sixty crossbred cows were assigned to one of two treatments: conventional (CONV) cows calved April/May and grazed cool-season grass in summer until weaning and grazed corn residue until next calving season. Alternate (ALT) herd cows were managed in confinement pens from early spring to fall, calved mid-summer, and calved in July/August, and grazed cover crops from fall to midwinter. Calves were weaned and cows grazed corn residue until returning to the drylot. Four groups of 20 cows were in each system. Calves from both production systems were weaned at the same days of age and grown in a drylot on a NEg =1.05 Mcal kg^{-1} diet (35% grass hay, 30% distillers grains (DG), 30% dry rolled corn (DRC), and 5% supplement NEg= 1.39 Mcal kg^{-1}) for 116 days. After growing, calves were transitioned to a high grain finishing diet (Year 1 – 34% DRC, 34% high-moisture corn (HMC, 20% DG, 7% grass hay and 5% supplement, NEg = 1.32 Mcal kg^{-1}), Year 2 40% HMC, 40% Sweet Bran, 15% corn silage, 5% supplement) and fed to 1.27 cm backfat. Each rep of calves from each system during the growing and finishing phases were put into a large pen-scale chamber that measured carbon dioxide (CO_2) and methane (CH_4) continuously for 5 days. The average CH_4 and CO_2 production per unit of feed intake was used to calculate total GHG emissions over the entire growing and finishing period. Calves from the ALT treatment were 45 kg smaller at weaning ($P < 0.01$) and had compensatory growth (1.21 vs 1.38 kg ADG $P < 0.01$) during the growing period but no differences in DMI ($P = 0.15$) compared to CON calves. Similar CH_4 and CO_2 production per animal and per kg DMI resulted in lower CO_2 and CO_2 per kg ADG ($P < 0.01$). During the finishing phase CONV calves had greater ADG (1.81 vs 1.52 kg ADG, $P < 0.01$) but similar DMI ($P = 0.25$). ALT calves were fed 35 d longer to achieve similar backfat which resulted in greater total CH_4 per animal across entire feeding period ($P = 0.02$) and greater total CO_2e ($P = 0.02$) for ALT calves. Methane production was greater in ALT calves (2.1 vs 2.5 kg CO_2e kg^{-1} HCW $P = 0.04$). Due to days to market, calves from the ALT cow system showed more global warming potential post-weaning when using both 23 and 4 for GWP of CH_4.

INTRODUCTION

The beef livestock sector is often scrutinized due to the perceived excessive production of greenhouse gases (GHG), particularly enteric methane (CH_4), which has been correlated with rising ambient temperatures and climate change (Valone 2021). In developing countries, producing food is estimated to be responsible for 34% of anthropogenic GHG emissions, whereas food production in developed countries was shown to be 24% of emissions (Crippa et al., 2021). Livestock production is thought to be responsible for 3.4 (EPA, 2011) to 14.5% of all GHG emissions (Ripple et al., 2014). One source of variation in such estimates is the specific ways of accounting for sources, sinks, and global warming potential (GWP) of various gases. Previous methods, for example, only accounted for the warming potential of CH_4 with no regard for its activity in the atmosphere over time, despite the strong dependency of GWP values on the time horizon used. Newer methods of measuring short-lived pollutants, such as CH_4 which is converted to CO_2 in the atmosphere in 9 to 12 years, while CO_2 itself can stay in the atmosphere for thousands of years (Allen et al., 2018, Balcombe et al., 2018, Cain et al. 2019, and Smith et al., 2018). These newer methods include GWP* which is an equation that estimates the GWP of CH_4 based on the time horizon and previous emissions. Another example is using the GTP (global temperature change potential) which also varies based on the time horizon used from 4 to 199 x CO_2 (Balcomb et al., 2018).

Recent modeling shows the proportion of GHG emissions from food production has remained unchanged from 1990 to 2020 (Crippa et al., 2021) despite large increases in food production. However, increasing atmospheric temperature, carbon dioxide (CO_2), and CH_4 concentration worldwide give urgency to investigating methods to reduce GHG emissions. A positive correlation exists between CH_4 production and dry matter intake (DMI) and forage intake (Beauchemin et al., 2010, and NASEM 2016), and a negative correlation with concentrate inclusion (Beauchemin et al., 2008). Diets containing high levels (>40%) of forage result in greater CH_4 production per kg of intake, per calorie of energy intake, and kg of gain or production, but not necessarily animal^{-1} day^{-1}(Winders et al., 2020). Carbon dioxide is a GHG, which is also naturally produced by cattle during respiration. While not as potent as CH_4, a greater understanding of CO_2 production is important when quantifying the total GHG production of beef systems. Often CO_2 production is ignored in GHG budgeting as respiration is considered biogenic carbon naturally recycled (IPCC, 2006). New methods in GHG measurement using eddy covariance method simultaneously measure the CO_2 and CH_4 flux into and out of an ecosystem (McGinn et al. 2014, Felber et al., 2016, Gourlez et al., 2018, Teague, et al, 2016). The carbon that is incorporated into the system can originate from CO_2 or CH_4 that has been converted into CO_2. Consideration of CO_2 from respiration as a GHG allows for accounting for all CO_2 release which is needed when considering C sequestered vs C emitted by the system (Dumortier et al., 2021, Felber et al., 2016, Gourlez et al., 2018, Stanley et al., 2018). From these new measurements of carbon sequestration, this paper quantifies CO_2 from animal respiration as a GHG. The C release from these two systems will be used to calculate sequestration needed by grazed lands outside of the post-weaning drylot system to maintain carbon balance.

Many models of GHG emissions have been created to estimate total emissions from cow/calf, stocker/backgrounding, and feedlot segments and the contributors within those sectors. Although GHG production by cattle consuming diets of various quality has been measured and summarized (Beauchemin et al. 2008, NASEM 2016) there are no direct known comparisons of GHG production of the same cattle with similar genetics produced in separate beef systems. Models have been developed to estimate GHG emissions from different sectors of the beef industry (Basarab 2012, Beauchemin et al., 2010 and Rotz et al. 2019). In addition to measures of beef system GHG production, measures of cattle performance have been conducted through weaning (Anderson et al., 2013 and Burson 2017) backgrounding (Neira et al, 2019), and feedlot phases (Carlson 2021, Cole, 2015, Gardine et al., 2018). Limited data exists investigating subsequent finishing performance and carcass characteristics. .

This study was designed to complement the findings from past studies and to help fill the existing knowledge gaps. The overall objective is to measure post-weaning GHG production from calves raised in different beef systems when consuming a high forage growing diet or a high concentrate finishing diet and the following specific goals:

1. Quantify the amount of GHG produced per unit of beef produced in two beef systems in the post-weaning phase.

2. Compare CH_4 and CO_2 emissions from cattle consuming forage-based or grain-based diets.

3. Estimate the needed sequestration per acre and land area needed to offset emissions from the post-weaning phase in these two systems.

MATERIALS AND METHODS

Facilities and management procedures used in this experiment were approved by the University of Nebraska – Lincoln Institutional Animal Care and Use Committee (IACUC # 1491). This experiment was conducted over 2 years at the Eastern Nebraska Research and Extension Center (ENREC) near Mead, Nebraska. Multiparous, cross-bred beef cows (n = 160; average age = 6.2 ± 2.8 years old) were utilized in a randomized complete block design with two treatments. Cows originated from two separate herds at ENREC and were managed in spring-calving, pasture-based systems. In year 1, cows were blocked by cow age, stratified by age and origin source (two sources), and assigned randomly within strata to one of two production systems treatments with four replicates. Once allocated to treatment and replicate, cows remained in assigned treatment for both years of the experiment. Post-weaning practices remained the same for all calves (steers and heifers). The CONV system was pasture-based. Cow/calf pairs grazed bromegrass pastures from April 25 to October 15, calved between April 15 and June 15, and weaned October 15 when calves were 168 days of age on average. After weaning, cows grazed corn residue until March 15, then returned to grass pastures and were fed grass hay until forage growth was adequate for grazing. The ALT system was an intensive, drylot-based system during the summer and grazing during the fall and winter. Dry, gestating cows entered the drylot on March 15 and were limit-fed an energy-dense diet from March 15 until calving which occurred July 15 to September 15. Cow feed intakes were adjusted to meet gestation and lactation requirements (NASEM, 2016). After calving, cow/calf pairs grazed secondary annual forage crop (fall oats) from October 15 to January 15, when calves were weaned. Following weaning, ALT cows grazed corn residue from January 15 until March 15. Calves from both systems were fence-line weaned for 5 days and limit-fed at 2% of bodyweight (BW) a diet of 50% alfalfa hay and 50% Sweet Bran (DM-basis). Cattle were weighed 2 consecutive days (Stock et al., 1983 and Watson et al., 2013) before starting a growing period (113 d year 1, 120 d year 2) and fed 35% grass hay (GH), 30% modified distillers grains plus solubles (MDGS), 30% dry-rolled corn (DRC), and 5% supplement (DM basis) for *ad-libitum* intake (Table 1, diet NEg = 1.05 Mcal kg^{-1} DM). When the growing period ended, cattle were limit-fed at 2% BW a diet of 50% alfalfa and 50% Sweet Bran for 5 consecutive days and weighed 2 consecutive days to determine initial body weight for the finishing phase. Following weighing, cattle were adapted to a high grain finishing diet using 4 step-up diets over 24 days. Diets during the finishing phase were different for years 1 and 2 (Year 1 – 1.39 Mcal NEg kg^{-1} DM, 34% DRC, 34% high-moisture corn (HMC), 20% DG, 7% GH and 5% supplement, Year 2 –

1.32 Mcal NEg kg^{-1} DM, 40% HMC, 40% Sweet Bran, 15% corn silage, 5% supplement). In the current study, cattle were finished to a targeted 1.52 cm of backfat between the 12th and 13 rib. Due to back fat variation within the pen, calves within the pen were allotted to one of two shipping dates. These dates were based on back fat thickness determined by ultrasonography between the 12th and 13th rib. Ultrasound images were acquired using an Aloka SSD-500V (Hitachi Healthcare Americas) and were processed by The CUP Lab (Ames, IA). A regression of increasing back fat over days on feed was determined and the number of days until the harvest was calculated (data not shown). The ALT cattle were on feed for 154 and 196 d (first and second shipping dates, respectively; year 1), for a weighted average of 174 d. The TRAD cattle were on feed for 145 and 173 d (first and second shipping dates, respectively; year 1), with a weighted average of 156 d. In year 2, ALT cattle were on feed for 154 and 210 d (first and second shipping dates, respectively), with a weighted average of 161 d. In year 2, TRAD cattle were on feed for 120 and 155 d (first and second shipping dates, respectively), with a weighted average of 125. Two years of calf crops from both CONV and ALT were monitored during the growing and finishing phases.

GHG Measurements

A large pen-scale chamber was developed to measure CH_4 and CO_2 using the difference in incoming and outgoing concentrations of CO_2 and CH_4 .and a flow rate. A full description of this method is described in Winders et al. (2020). Gas concentrations were analyzed using an LI-7700 CH_4 analyzer and LI-7500DS CO_2 /H_2O Analyzer (both LI-COR Biosciences, Lincoln, NE). Schematic of chamber layout and visualization of data is presented in Figures 1 and 2. The methane analyzer operates using near-infrared laser and wavelength modulation spectrometry to detect the absorption of CH_4 in the air sample. The resolution of this instrument is 5 ppb at 10 Hz, in typical ambient concentrations (2 ppm CH_4). The carbon dioxide analyzer uses nondispersive infrared spectroscopy to measure CO_2 and water densities in the air sample. The air sampling system cycled between 3 sampling lines; one line in each chamber (east and west) and one line outside, located on the south side for ambient air supply which corresponds to ambient air inlet to the pen chambers. Each cycle was 20 minutes during which each side of the barn and ambient air was sampled. Data were captured at 1 Hz. Concentrations of CH_4 and CO_2 were dramatically different between the 4 sampling points for each 20-minute cycle. The start of the first 20-minute interval was determined for each day's data based on the change in air concentration. Data before the start were removed (between 0 and 19 min per day) then using high throughput software (R Foundation, Indianapolis, IN) that calculated the mean concentration of CH_4 and CO_2 during each source sampling within every 20-minute cycle. From these data, the mean concentration of CH_4 and CO_2 was calculated. Data were further processed so that the 24-hour period from feeding to feeding was considered a day. Feeding times were recorded by feeding software in the feed delivery truck. Air was pulled through each pen and exits through the fans, with a sampling line positioned above the fans. Fans were evaluated twice for airflow rate, once prior and once after the trials (FANS System, Iowa State University). Airflow through the chambers with two fans running was 1,274 L/s. Air was sampled in each pen using a sampling line with a pump and controlled with a solenoid system and data logger. Solenoids switch sampling between the ambient line, pen 1, and pen 2, allowing for each pen to be sampled for 6 min. After cycling through the sampling of the two pens and ambient air, an additional ambient air sample was collected for 2 min to complete a 20-min cycle. A 2-min ambient sampling allows for easy recognition of when the cycle resets when data were being analyzed as pen 1 always follows the 2-min sampling period. An adequate time of 6 min allows for the system to be flushed between pen 1 and pen 2 sampling periods and provide ambient concentrations of CO_2 and CH_4. Emissions data were averaged across each 6-min time point, excluding the first 60 s to avoid including lower measurements as gas acclimates to solenoid switching. Gas production per day was an average of all of the 6-min measurements per pen for a 24-h feeding period.

Calves from one pen were split evenly between both chambers of the barn after sorting to equalize heifers and steers in each chamber. After 5 days, calves were removed, and the manure that accumulated over the previous 5 days was monitored for GHG emissions for 24 hours. On the 7th day, manure was removed from the barn using a skid loader, and then a final 24 hour measurement of the empty barn with no manure or cattle was performed for baseline measurements. The GHG production from manure was calculated by the difference from baseline. It was assumed that the GHG contributions from manure were equal to one-half of what was measured during the 24 hours, since, on average, half of the accumulated manure was present in the barn at any one time during the 5-day measurement period. The GHG contribution from manure was subtracted from the total GHG emissions to determine GHG emissions from the cattle. This correction was small, averaging 1.32 g of CH_4 and 130 g of CO_2 animal^{-1} day^{-1}. When the 7-day cycle was complete, the cycle was repeated for the other 3 replications in the production system. Calves from both CONV and ALT systems were in the barn for the same days on feed within a year, on average, for both growing and finishing, but were at different times of the year between systems due to differing calving dates.

Across the 2 years of data collection, a total of 80 measurement days were acceptable (each day contains approximately 70 measurements one for every 20 minutes for each chamber). Six days were not used due to incomplete data, power outages, or malfunctions with the sensor system. Total production (grams animal^{-1} day^{-1}) was analyzed as an ANOVA using PROC MIXED, with day in the barn as the repeated measure. There were 5 days of measurements each time cattle were in the barn. The means of the 5 days of CO_2 and CH_4 production from each chamber were used to calculate GHG production from each replicate within groups. These were used to calculate CO_2 and CH_4 emissions expressed per kg of DMI. The CO_2 and CH_4 values per kg of DMI were used to calculate grams of CO_2 and CH_4 per kg of gain, per animal daily, and the total over the entire feeding period based on average intake from each replicate. To estimate global warming potential (GWP) CH_4 values were multiplied by 4 (Balcombe et al., 2018) or 23 (IPCC 2013) to calculate CO_2 equivalents (CO_2e). Cattle in CONV and ALT were slaughtered at equal backfat thicknesses, but groups had different numbers of days on feed and different feed intakes. Differences in CH_4 and CO_2 production between beef systems treatment were analyzed using the MIXED procedure of SAS (SAS Institute, Inc., Cary, NC) with the pen as the experimental unit and year as a random variable. Statistical comparison between cattle consuming growing or finishing diets was analyzed with diet and treatment as fixed effects and year as a random effect. Treatment x diet interactions were analyzed. Means were considered statistically significant when $P < 0.05$ and a tendency when $0.05 \leq P \leq 0.10$

RESULTS AND DISCUSSION

Growing

During the post-weaning growing period, no difference in DMI was observed (*P* = 0.15; Table 2). However, a 14.2% greater ADG was observed in the ALT calves which resulted in a 17.6% increase in G:F (P < 0.01). Calves from the ALT system were 45 kg lighter at weaning (P< 0.01). Pasture-based systems compared to confinement-based systems have shown 17 to 18 kg lower in weaning BW (Anderson et al., 2013 and Burson 2017). Warner et al. (2019) observed drylot calves were 23 kg heavier at weaning, and calves raised in a grazing system had compensatory growth during the growing phase. Neira et al. (2019) observed greater wean BW for confinement-based calves, but this was likely due to drought conditions in the pasture system. The ALT system may result in lower BW at weaning due to differences in nutrient intake prior to secondary annual forage turnout, weather, and differences in diet quality both in confinement and grazing secondary annual forage. Lower feed intake relative to CONV, especially in confinement, is a theory for lower performance pre-weaning in ALT calves. Perry et al. (1974) showed no differences in weaning BW in confinement vs. pasture-based systems. However, lower ADG in confinement calves 90 to 120 d of age could have occurred because of competition at the feed bunk. Cole et al. (2015) compared an extensive system utilizing winter range and protein supplementation to an intensive system. The intensive system supplemented prairie hay to cows and then full access to wheat pasture in the final 40 days while calves always had full access to wheat pasture. The steer calves from the intensive system had greater weaning weight and post-weaning ADG and G:F in the feedlot period.

Greenwood and Café (2006) observed compensatory gain during the backgrounding period in calves under nutrient restriction pre-weaning. Calves were 66 kg lighter at weaning and had similar ADG, but lower DMI in the backgrounding. In addition heifer calves that were nutrient restricted were 65 kg lighter at weaning but only 25 kg lighter at 30 months of age. A theory of compensatory growth is lower maintenance requirement due to lower visceral mass (Yambayamba et al., 1996) as a result of feed restriction and greater protein synthesis followed by increased fat deposition (Hornick et al. 2000). The compensatory gain in calves measured pre and post weaning has been observed in others (Carlson 2021, Gillespie 2013) comparing calves that were lighter at weaning or lighter due to the lower plane of nutrition prior to compensatory growth. The greater gain in ALT calves during the growing phase is consistent with others in the literature and resulted in subsequent effects on methane relative to performance measures.

During the growing phase, methane production animal^{-1} d^{-1} and kg^{-1} DMI were not different (P = 0.79 and 0.62, respectively) between CONV and ALT. Due to differences in ADG, the g CH_4 kg^{-1} ADG was 16.5% lower in ALT calves. Total CH_4 over the growing period (16.7 and 15.9 kg for CONV and ALT, respectively) was not statistically different (P = 0.31) due to the same days on the feed but no differences in emissions per day. Carbon dioxide was not different animal^{-1} d^{-1} or kg^{-1} DMI, but was 22% lower in g CO_2 kg^{-1} ADG in ALT calves due to smaller BW in the growing period ($P < 0.01$). There was a tendency (P = 0.07) for total CO_2 animal^{-1} to be greater in CONV calves. When considering total CO_2e there is a tendency (P = 0.11) for CONV to have greater CO2e (1063 and 968 kg CO_2e for CONV and ALT, respectively CH_4 23x CO_2).

The result was the same when expressing CH4 with lower GWP values (4x CO_2), 746 and 667 kg CO_2e for CONV and ALT, respectively. In addition, no differences in GE intake, GE loss from methane, or GE loss from methane as a percent of GE intake. These data indicate that the system did not affect GHG emissions insofar as making ALT calves less methanogenic but did change methane per unit of growth due to advantages in daily gain and efficiency.

Finishing

The finishing period showed the opposite trend of the growing period (Table 3). Again, DMI was not different, but ADG was greater in the CONV steers ($P < 0.01$) and resulted in a greater G:F ratio ($P < 0.01$). There is no evidence this observation was due to incorrect starting weights at weaning or the start of finishing. Gillespie et al. (2013) backgrounded heifers with low or high levels of DGS supplementation on corn residue and supplement or no supplement on pasture in a 2x2 design. The compensatory gain was observed in the summer phase by heifers that received less supplementation over winter. In reverse, heifers that received more supplementation during winter but gained less over the summer phase gained more during the finishing phase and compensated above highly supplemented summer heifers. This is similar to what was observed by CONV calves that gained less during the growing phase but more during the finishing phase.

A statistical tendency ($P = 0.10$) in methane production animal^{-1} day^{-1} was observed for CONV and ALT (125 and 145 g animal^{-1} day^{-1}, respectively). Total methane animal^{-1} over the finishing period was 47% greater in the ALT calves ($P = 0.01$) as well as total CO_2e ($P < 0.01$ or $P = 0.02$ for 23x or 4x CO_2e, respectively). This was primarily due to greater DOF in ALT vs CONV (183 vs 148, respectively). The resulting DOF is an important distinction that has a profound effect on models predicting GHG. White and Capper (2013) modeled the economic and environmental impacts of improving ADG or final weight (FW) by 15%. These improvements would decrease, per unit of beef produced, total CH_4 12.8 and 15.9% and total CO_2e by 11.7 and 13.7%, respectively for ADG and FW. Improving ADG but maintaining the same FW would decrease days on feed. Each day an animal is on feed requires more feed and production of GHG. Maintaining ADG but improving FW would increase the amount of product when calculating carbon per unit of product. In the case of this system, lower BW at the start of the growing period results in lower BW at the end of the period despite greater ADG. Greenwood and Café (2006) observed calves with differentiating growth throughout their life. Calves that were nutrient-restricted preweaning maintained lower BW to slaughter and had 25 kg lower HCW. However, the restriction during preweaning had no effect on growth during the finishing phase. Regarding methane production, feed restriction has been shown to up-regulate the activity of some methanogens, while also to decrease the activity of others (McGovern et al. 2017).

During the finishing phase similar fatness was achieved for ALT and CONV, but at numerically lower BW for ALT calves. This gives weak evidence that lower BW at weaning in ALT calves affected physiological maturity since it required more days and greater body weight to achieve the same fatness. Gross energy intake and GE loss % due to methane were not different between treatments ($P = 0.26$ and 0.14, respectively). There was a tendency for GE loss in Mcal day^{-1} to be greater in ALT likely due to numerically greater methane production per kg^{-1} DMI and day^{-1}.

Combined Growing and Finishing

When analyzing data from the entire feeding period, CONV calves were 44 and 24 kg heavier at the start of growing and finishing, respectively (Table 4). At slaughter, CONV calves were 10 kg lighter, but had greater back fat depth (1.65 vs 1.51 cm respectively, $P = 0.05$) even though ALT calves were fed 35 days longer, on average. Across the entire feeding period, there were no differences in DMI, G:F or ADG. Gross energy intake (Mcal d^{-1}), loss from CH_4 (Mcal d^{-1}), and CH_4 loss (% of GE) were similar between treatments ($P = 0.27$, 0.23, and 0.27, respectively). Methane production was similar across treatments for both g kg^{-1} DMI, and g $animal^{-1}$ d^{-1} ($P = 0.17$ and 0.26, respectively). Greater days on feed increased total methane by 22% ($P = 0.02$) and methane kg^{-1} of HCW by 20% ($P = 0.04$), respectively, in ALT calves. There was a tendency for CO_2 production day^{-1} and kg^{-1} DMI to be greater for CONV calves ($P = 0.10$). This was likely driven by greater BW across the feeding period in CONV calves producing more CO_2 from maintenance metabolism. Again, due to more days on feed, the higher daily CO_2 values were not observed in the ALT calves but more CO_2 was emitted over the feeding period resulting in no statistical differences in total CO_2 $animal^{-1}$ or CO_2 kg^{-1} HCW (P = 0.22 and 0.44, respectively).

Using traditional values for GWP (23x CO_2) total CO_2e kg^{-1} HCW were 6.9 and 7.5 for CONV and ALT ($P = 0.10$) respectively. Methane-only CO_2e were 2.12 and 2.55 kg^{-1} HCW ($P = 0.04$) for CONV and ALT, respectively. Total CO_2e across the feeding period were 2,680 and 2,971 kg ($P = 0.02$) for CONV and ALT, respectively. New values taking in to account the breakdown of CH_4 in the atmosphere (4x CO_2) decreased CO_2e from CH_4 but the same statistical differences in CO_2e total and kg^{-1} HCW are observed. Stackhouse-Lawson et al. (2012) did a carbon life-cycle assessment of farm gate

California beef systems. The stocker and feedlot portions of CH_4 production added to 1,279 kg CO_2e on 354 kg HCW which is 3.61 kg CO_2e per kg HCW from methane. This is greater than the measured value in the current study due in part because the projected CH_4 production per day was 218 and 95 for stocker and finisher in Stackhouse-Lawson et al. (2012), respectively compared to 122 and 135 g animal^{-1} d^{-1} observed for growing and finishing on average across both systems. For Stackhouse-Lawson et al. (2012) total production system CO_2e from conception to slaughter was 9,416 kg which is 26.6 kg CO_2e per kg HCW. What is not included in our estimate are N_2O emissions, which have a GWP of 234 to 298 times that of CO_2. These accounted for an additional 1,837 kg CO_2e and accounted for 20 and 35% of all GHG emissions in backgrounding and finishing in their analysis, respectively in Stackhouse-Lawson et al (2012).

Diets

When comparing cattle on growing or finishing diets (Table 5) there was a 1.9 kg increase DMI ($P < 0.01$), statistically significant for interaction between treatment and diet ($P = 0.10$). In Tables 2 and 3, the variables driving the interaction are numerically greater DMI in CONV during growing and numerically greater DMI in finishing for ALT calves. This same interaction was observed for ADG ($P < 0.01$) and G:F ($P = 0.2$). Resultingly, no comparison can be made using diet as the main effect due to statistically significant interactions for CH_4 kg^{-1} ADG, total CH_4, CO_2 kg^{-1} ADG, and total CO_2. These interactions appear to be driven by the difference between system treatments for ADG in the growing and finishing phases. Illustration of this interaction in GWP of the diets is shown in Figures 3 and 4. No statistical difference in CH_4 production per day ($P = 0.59$) was observed between growing and finishing diets. Winders et al. (2020) reported

156 and 132 g per animal per day for growing and finishing, respectively. The higher emissions by Winders et al. (2020) are likely explained by greater amounts of total roughage in the diet (75%) as opposed to the moderate level of forage in the growing diet (35%) in the growing diet of the current study. Differences in DMI and ADG between growing and finishing diets drive subsequent differences in CH_4 kg^{-1} of DMI and ADG. The interaction between CH_4 production in growing and finishing diets kg^{-1} ADG and DMI is not due to differences in CH_4 production but is due to differences in animal performance.

Other studies which investigated CH_4 production in both growing and finishing diets found similar results. Lower CH_4 kg^{-1} DMI has been shown in other studies when comparing forage-based growing diets and high-concentrate finishing diets were fed to the same cattle in succession. Decreases of 39%, 32%, and 32% were observed for Vyas et al. (2016), Vyas et al. (2018), and Winders et al. (2020) in CH_4 kg^{-1} DMI. In each of these cases, the finishing diet replaced forage with concentrate. Methane emissions per unit of ADG (108.5 and 81.6 g per kg ADG) for growing and finishing were comparable to Winders et al. (2020) who observed amounts of 155 and 79 g per kg ADG, respectively. Vyas et al. (2018) fed diets with or without monensin and 3-nitrooxypropanol (NOP) in both growing and finishing diets in a 2x2 factorial design. In the non- NOP diets with monensin, a 17% increase in ADG and a 41% increase in DMI were observed in finishing diets compared to growing diets. In the finishing study of Vyas et al. (2018) methane $animal^{-1}$ d^{-1} was 13% greater than the growing portion of the study. Improvements in ADG and DMI resulted in a 32% reduction in CH_4 kg^{-1} DMI and a 4% improvement in CH_4 kg^{-1} ADG. In the current study, no difference was observed in CH_4 $animal^{-1}$ d^{-1} but a 31% decrease in CH_4 kg^{-1} DMI.

In the current study CH_4 kg^{-1} DMI decreased 21% in finishing diets. Methane in CH_4 per d^{-1}, kg^{-1} DMI, and kg^{-1} ADG were only 3.3, 21, and 24.8% less in finishing. Winders et al. (2020) fed growing diets of 45% alfalfa, 30% sorghum silage, 22% MDGS, and 3% supplement. A 72% increase in ADG, 39% increase in DMI, and 20% increase in G:F was observed when cattle transitioned to a diet of 33% DRC, 33% HMC, 15% WDGS, and 15% corn silage which was similar to the diet fed in year one of the current study. The interaction in treatment and diet may cause some variation in these results relative to Winders et al. (2020) who observed decreases in 15, 31, and 21% in for methane in CH4 d^{-1}, kg^{-1} DMI, and kg^{-1} ADG, respectively.

Production of CO_2 kg^{-1} DMI was 9.9% greater ($P < 0.01$) in finishing compared to growing.   Winders et al. (2020) ad Vyas et al. (2018) observed a 31% and 17% increase in CO_2 kg^{-1} DMI when feeding a growing diet compared to finishing diets. Carbon dioxide emissions day^{-1} were 33% greater in finishing cattle ($P < 0.01$). The same is true in this study as well as Winders et al (2020) and Vyas et al. (2018) who observed 65% and 60% increases in CO_2 $animal^{-1}$ day^{-1}, respectively, when comparing growing cattle to finishing cattle. When using GWP of 23 for CH_4, CO_2e per day was 19% greater ($P < 0.01$) in finishing which was driven by increases in DMI and CO_2 production from greater respiration required by cattle with heavier BW. Greater CO_2 generated from metabolism in finishing cattle that were heavier than cattle consuming a growing diet. No difference in CO_2 kg^{-1} ADG was observed between growing and finishing diets, but an interaction (P= 0.01) was observed with diet and treatment indicating that cattle in each system produced different amounts of CO_2 when consuming the same diet. As discussed earlier, this was likely due to greater BW in CONV in growing and finishing periods.

Total CO_2e d^{-1} for finishing and growing diets are presented in Table 5. When using 4 or 23 for the GWP for CH_4, this did not change the conclusion for comparing growing and finishing diets. In the current trial growing diets were responsible for 40.8 and 38.4% CO_2e for 4x CO_2 and 23x CO_2, respectively. On average, a greater amount of CO_2e originates from the finishing period due to more DOF. In a life-cycle assessment by system Stackhouse-Lawson et al. (2012), when calculating total CO_2e, the cow/calf, stocker, and feedlot sectors were responsible for 79, 16, and 5% of the methane but 69, 14, and 17%, respectively of the CO_2e from a theoretical California beef system. Modeling U.S. beef production across 7 different regions Rotz et al. (2019) hypothesized that GHG emissions accumulated 39%, 31%, and 30% from cow/calf, stocker, and feedlot sectors. These proportions are variable due to differences in forage type, diet quality, stocking rates, and days from weaning to slaughter and animal performance.

Basarab et al. (2012) estimated post-weaning emissions of calf-fed and yearling-fed beef production systems and with or without the use of exogenous hormones. Calf-feds were put in the feedlot immediately after weaning and yearling-fed were backgrounded on fall pasture (42 days), winter backgrounding (191 days), and summer pasture (66 days) for a total of 299 days before being put into the feedlot. All on-farm fossil fuel use was estimated for feed production. Calf fed no implant, calf-fed implant, yearling no implant, and yearling implant treatments over a 2-year period averaged 11.4, 10.7, 11.8, and 11.2 kg CO_2e kg^{-1} HCW from CH_4 alone. Putting cattle directly into the feedlot post-weaning decreased carbon footprint 2.7% per kg HCW compared to backgrounding for 299 days. In the current study, all calves were treated equally. However, given the greater gains and G:F ratio in the finishing period, fewer days being fed a high forage diet would likely result in less total CO_2e from methane.

Pelletier et al. (2010) completed a life cycle assessment for U.S. Midwest beef systems. The finishing portion investigated grass-based or grain-based practices. Gains assumed in these systems were low, 1.4 and 0.9 kg per day which led to more days on feed, 303 and 450, respectively. The present study required 116 and 166 days during the growing and finishing periods, respectively. Pelletier et al. (2010) calculated and 340 and 152 tonnes CO_2e for backgrounding/feedlot or a feedlot from animal sources in a total farm system that produced 75 calves. This calculates to 134 and 38 g CH_4 animal^{-1} day^{-1}. The CH_4 contribution of CO_2e was calculated as 11.5 or 8.9 kg CO_2e kg^{-1} HCW for backgrounding/feedlot or feedlot-based systems, respectively. While average feed intake used is not reported, large differences in CO_2e from methane are observed between the present study and Pelletier et al. (2010) due to differences in animal performance and days on feed. They estimated methane production to be 218 and 95 g animal^{-1} day^{-1} for stocker and backgrounding phases, respectively. Days on feed for stocker and feedlot were 182 and 121 days, respectively. Methane-only CO_2e from these systems, assuming a 354 kg HCW, would produce 2.57 and 0.74 kg CO_2e per kg HCW for stocker and finishing phases, respectively. The greater CO_2e from methane in the growing phase is due to greater DOF.

Based on CH_4 alone, the percent of CO_2e per kg HCW post-weaning was 41.8 and 58.2% for growing and finishing, respectively in the present study. Stackhouse-Lawson et al. (2011) calculated that backgrounding systems produced 60% while finishing 40%.

Rotz et al. (2019) calculated GHG emissions across 7 geographic regions of the U.S. and found backgrounding systems produced 54% while feedlot 46%. While days on feed are variable in these scenarios between the systems, both models assume higher forage diets in backgrounding relative to feedlot leading to more methane. All models of GHG emissions are subject to critique due to overarching assumptions of production, management, and emissions that do not apply in all scenarios. Calculating the emissions not directly associated with enteric fermentation or animal respiration is beyond the scope of this paper, however, our values for total emissions from fermentation are comparable to other models in the literature.

Carbon sequestration

The CONV system cows graze brome pasture from early May to weaning in October. The pasture is the area available to sequester carbon with the potential to offset animal emissions from the entire system (1.21 ha animal^{-1}). In the ALT system, the sequestered area is the oat cover crop grazed from late October to mid-January (1.05 ha animal^{-1}). Assuming GWP of CH_4 as 23, needed C sequestration for the is 24 and 25.1 g C m^{-2} yr^{-1}. For CONV and ALT, respectively (Table 6). Needed C sequestration is reduced to 16.8 and 17.3 g m^{-2} if GWP of CH_4 from the system is 4x CO_2e. Sequestration needed to offset finishing period CH_4 and CO_2 is 34.8 and 49.8 during the finishing period for CONV, and ALT respectively and 27 and 36.5 g C m^{-2} for GWP of 4x CO_2, respectively. Felber et al. (2016) measured C sequestration of 68 g C m^{-2} of dairy cows grazing grass/clover mixture. Assuming the sequestration in the CONV and ALT systems are equal to Felber et al. (2016) on bromegrass and oat cover crop m^{-2} of pasture, the areas needed to sequester CO_2 and CH_4 emissions from the growing period are equal to 0.43 and 0.39 ha animal^{-1} for CONV and ALT, respectively. During the finishing period, the area needed is 0.62 and 0.77 ha animal^{-1}. Using 4 as the GWP needed area (Table 7) for the growing period is reduced to 0.30 and 0.27 ha animal^{-1} and 0.48 and 0.56 ha animal^{-1} during the finishing period for CONV and ALT, respectively. Felber et al. (2016) measured C sequestration after accounting for CO_2e from animal respiration and CH_4 production. Using this value for both CONV and ALT, 0.43 and 0.39 ha animal^{-1} would be required to offset emissions during the growing period. Other emissions not measured in this study include soil and manure nitrous oxide (N_2O) and CO_2 produced from burning fossil fuels during the production of feed and used in livestock production. These emissions account for 15% (Stackhouse et al., 2012) to 37% (Beauchemin et al. 2010) of all emissions. These life-cycle assessments did not consider CO_2 from cattle respiration as a GHG, but this is needed since all CO_2 can be sequestered into plant growth.

There are many factors that affect sequestration. McGinn et al. (2014) measured C sequestration from steers grazing mixture of wildrye, wheatgrass, blue grama, and spear grass. Stocking rates by McGinn et al. (2014) (10 or 20 ha animal^{-1}) were much lower than the bromegrass or oat forage grazing in the current study (1.2 or 1.05 ha animal^{-1}). McGinn et al. (2014) measured 4 g C m^{-2} sequestered at 10 ha animal^{-1} but a net production of C (9 kg CO_2e ha^{-1} yr^{-1}) after accounting for CH_4 GWP of 25. This increased to -338 kg CO_2e ha^{-1} yr^{-1} at 20 ha animal^{-1}. The difference between Felber et al. (2016) and McGinn et al. (2014) can be attributed to differences in grazing days, forage growth, stocking density, and forage type. The values needed for sequestration in CONV and ALT systems described above can be used to inform grazing strategies to maximize sequestration of C to offset CH_4 and CO_2 emissions from the post-weaning phase. Basarab et al. (2012) modeled C sequestration from all feed and pasture resources from on-farm production data. Pastures in the model sequestered between 20 and 50 g m^{-2} yr^{-1}. Other methods of accounting also counted C loss from grain production against the balance of C sequestration. This sequestration offset, on average, 12% of animal emissions. Measuring the production of CO_2 and CH_4 from the post-weaning phase in the current study can be used to compare the animal performance and emissions. More research is needed to quantify C sequestration from pasture and feed production as potential offsets of emissions from beef production. A deeper understanding of animal emissions throughout the production cycle can inform the selection of management strategies to achieve carbon balance.

IMPLICATIONS

This study examined two different beef productions systems and evaluated emissions from cattle weaned in these systems.

The conventional system:

1. Resulted in greater daily gain during the finishing period and greater carcass backfat
2. Less days on feed in the finishing period needed to finish cattle to 1.27 cm backfat
3. Produced more total CO_2e during the growing phase.
4. Required less carbon sequestration to offset emissions due to lower stocking density from cows grazing in the pre-weaning phase.

The partial-confinement system:

1. Lower body weight at weaning and at initiation of finishing phase
2. Compensatory growth in the growing period was observed.
3. More total CO_2e during the finishing phase were produced
4. Required more carbon sequestration per hectare or hectares per animal to offset emissions due to less days grazing annual forages

Overall, calves in the post-weaning period in the confinement-based system produced more total methane and CO_2 and, as a result, had greater global warming potential (measured in CO_2e). When considering the land area and carbon sequestration needed, the partial-confinement system required more land area to offset CH_4 and CO_2 produced by calves in the post-weaning period. Further research is needed to understand how beef systems can be developed to 1) minimize greenhouse gas production, 2) optimize animal performance and 3) maximize carbon sequestration from growing biomass within the system. Previous research, which has traditionally only focused on emissions, has concluded that beef production is contributing to buildup of atmospheric carbon. The emissions summarized from growing and finishing periods in this study quantifies emissions and needed sequestration to offset those emissions. Combining data from this study and previous work shows potential for carbon sequestration during the grazing portions of beef production to offset emissions produced when cattle are fed harvested feeds in confinement.

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TABLES

Table 2.1. Composition of diets (DM basis) fed to cattle during growing and finishing phases.

	Growing	Finishing	
Ingredients	Year 1 and 2	Year 1	Year 2
Dry Rolled Corn	30	34	
High Moisture Corn		34	40
Sweet Bran			40
MDGS	30	20	
Corn Silage			15
Ground Hay	35	7	
Supplement	5	5	5
Fine Ground Corn	2.5214	2.2925	1.8782
Limestone	1.977	1.69	1.63
Tallow	0.125	0.125	0.1
Urea	0	0.5	0
Salt	0.3	0.3	0.3
Beef trace mineral	0.05	0.05	0.05
Vitamin ADE	0.015	0.015	0.015
Rumensin 90	0.0116	0.0165	0.0165
Tylan 40	0	0.011	0.0102

Table 2.2. Performance and greenhouse gas production of cattle raised in conventional (CONV) or confinement (ALT)-based productions systems during growing period.

	CONV	ALT	SEM	*P*-value
Growing				
DMI, kg	8.9	8.7	0.1	0.15
ADG, kg	1.21	1.38	0.02	<0.01
G:F	0.1361	0.1600	0.486	<0.01
CH_4				
Per animal per day, g	121.8	122.9	3.42	0.79
Per kg DMI, g	16.12	15.74	0.53	0.62
Per kg ADG, g	118.39	98.77	5.58	<0.01
Total per animal, kg	16.69	15.88	0.76	0.31
[1]CO_2e from CH_4, kg	383.8	365.1	17.42	0.31
[2]CO_2e from CH_4, kg	66.8	63.5	3.0	0.31
CO_2				
Per animal per day, g	4948	4713	193	0.25
Per kg DMI, g	656.54	599.44	40.57	0.18
Per kg ADG, g	4823.71	3752.26	279.35	<0.01
CO_2e from CO_2, kg	679.48	603.28	39.42	0.07
CO_2e total, kg				
CH_4 23x CO_2	1063.4	968.3	55.5	0.11
CH_4 4x CO_2	746.3	666.6	42.1	0.07
GE intake, Mcal per d[3]	84.2	81.8	1.53	0.15
GE loss, Mcal per d	7.96	7.56	0.34	0.29
GE loss, %	9.48	7.26	0.4	0.62

[1] CO_2e calculated as kg CH_4 x 23

[2] CO_2e calculated as kg CH_4 x 4

[3] GE = gross energy

Table 2.3. Performance and greenhouse gas production of cattle raised in conventional (CONV) or confinement (ALT)-based productions systems during finishing period.

	CONV	ALT	SEM	*P*-value
Finishing				
DMI, kg	10.57	10.81	0.20	0.25
ADG, kg	1.81	1.52	0.03	<0.01
G:F	0.1701	0.1403	1.16	<0.01
CH_4				
Per animal per day, g	125	145.2	11.4	0.1
Per kg DMI, g	11.8	13.4	1.0	0.14
Per kg ADG, g	69.9	95.2	9.8	0.02
Total per animal, kg	18.4	27.0	3.1	0.01
[1]CO_2e from CH_4, kg	423.6	620.7	70.4	<0.01
[2]CO_2e from CH_4, kg	73.4	108.0	12.2	0.01
CO_2				
Per animal per day, g	7551	7111	352	0.23
Per kg DMI, g	717	662	35	0.14
Per kg ADG, g	1225	1424	174	0.06
CO_2e from CO_2, kg	1127	1294	65	0.02
CO_2e total, kg				
CH_4 23x CO_2	1546	1917	119	<0.01
CH_4 4x CO_2	1196.9	1403.7	74.3	0.02
GE intake, Mcal per d[3]	103	105	2	0.26
GE loss, Mcal per d	6.96	8.08	0.63	0.10
GE loss, %	6.70	7.70	0.59	0.14

[1] CO_2e calculated as kg CH_4 x 23

[2] CO_2e calculated as kg CH_4 x 4

[3] GE = gross energy

Table 2.4. Performance and greenhouse gas production of cattle raised in conventional (CONV) or confinement (ALT)-based productions systems during growing and finishing period.

	CONV	ALT	SEM	*P*-value
Growing and Finishing				
Initial Growing BW, kg	230	186	4	<0.01
Initial Finishing BW, kg	374	350	5	<0.01
Carcass adjusted Final BW[1], kg	604.6	615.1	7.7	0.19
HCW, kg	381	388	5	0.18
DMI, kg	9.8	9.9	0.1	0.45
ADG, kg	1.54	1.47	0.05	0.15
G:F	0.15	0.14	0.21	0.15
Back fat, cm	1.65	1.51	0.043	0.05
GE intake, Mcal per d	92.3	90.8	1.38	0.27
GE loss, Mcal per d	7.54	7.77	0.23	0.33
GE loss, %	7.82	8.23	0.35	0.27
CH_4				
Per animal per day, g	132.7	141.9	6.37	0.17
Per kg DMI, g	6.12	6.44	0.28	0.26
Total per animal, kg	35.1	42.9	2.9	0.02
Per kg HCW, g	92.2	110.7	8.3	0.04
CO_2				
Per animal per day, g	6805	6359	255	0.1
Per kg DMI, g	693.5	640.2	29.43	0.09
Total per animal, kg	1803.0	1899.0	74.0	0.22
Per kg HCW, g	4736.8	4913.9	224.9	0.44
CO_2e total, kg				
CH_4 23x CO_2	2609.4	2885	109	0.02
CH_4 4x CO_2	1943.2	2070.3	77.9	0.12
CH_4 23x CO_2				
CO_2 only CO_2e per kg HCW, kg	4.737	4.914	0.226	0.45
CH_4 only CO_2e per kg HCW, kg	2.117	2.546	0.191	0.04
CO_2e per kg HCW, kg	6.854	7.460	0.340	0.10
CH_4 4x CO_2				
CO_2 only CO_2e per kg HCW, kg	4.737	4.914	0.226	0.450
CH_4 only CO_2e per kg HCW, kg	0.370	0.443	0.033	0.04
CO_2e per kg HCW, kg	5.110	5.360	0.24	0.32

[1] HCW divided by dressing percent (0.63)

Table 2.5. Performance and greenhouse gas production of cattle consuming growing or finishing diets.

				P-value		
	GROWING	FINISHING	SEM	Diet	TRT	DietxTrt
DOF	117	166				
DMI, kg	8.8	10.7	0.14	<0.01	0.95	0.10
ADG. Kg	1.30	1.66	0.07	<0.01	0.36	<0.01
G:F	0.148	0.1552	0.005	0.19	0.59	<0.01
CH_4						
Per animal per day, g	139.7	135.1	8.23	0.59	0.43	0.11
Per kg DM, g	15.9	12.6	0.7	<0.01	0.42	0.19
Per kg ADG, g	108.5	81.6	5.7	<0.01	0.63	<0.01
Total CH_4, kg	16.3	22.7	1.7	<0.01	0.03	0.01
Total CO_2e, kg	374.4	521.9	39.6	<0.01	0.03	0.01
CO_2						
Per animal per day, g	5506	7339	277	<0.01	0.05	0.76
Per kg DM, g	628.1	690.0	31.7	0.06	0.08	0.99
Per kg ADG, g	4288.0	4570.2	260.1	0.29	0.14	0.01
Total CO_2, kg	641.3	1209.5	50.4	<0.01	0.35	0.02
CO_2e (CO_2 and CH_4) 23x CO_2						
CO_2e per animal per day, kg	9.00	10.71	0.33	<0.01	0.25	0.18
CO_2 kg^{-1} DMI, kg	1.026	1.004	0.04	0.54	0.28	0.49
CO_2e kg^{-1} ADG, kg	6.79	6.47	0.31	0.32	0.32	<0.01
CO_2e total, kg	1016	1731	64	<0.01	0.04	<0.01
CO_2e total kg^{-1} HCW, kg	2.646	4.511	0.18	<0.01	0.11	<0.01
CO_2e from CH_4, kg^{-1} HCW, kg	0.975	1.356	0.38	<0.01	0.06	0.01
CO_2e from CO_2, kg^{-1} HCW, kg	1.671	3.155	0.14	<0.01	0.53	0.03
CO_2e (CO_2 and CH_4) 4x CO_2						
CO_2e d^{-1}, kg	6.07	7.87	0.28	<0.01	0.07	0.58
CO_2 kg^{-1} DMI, kg	0.692	0.740	0.03	0.15	0.11	0.88

CO_2e kg^{-1} ADG, kg	4.72	4.90	0.27	0.52	0.18	<0.01
CO_2e total, kg	707	1300	51	<0.01	0.22	<0.01
CO_2e total kg^{-1} HCW, kg	1.841	3.390	0.140	<0.01	0.39	0.02
CO_2e from CH_4, kg^{-1} HCW, kg	0.170	0.236	0.07	<0.01	0.06	0.01
CO_2e from CO_2, kg^{-1} HCW, kg	1.671	3.155	0.140	<0.01	0.530	0.030

Table 2.6. Carbon sequestration required when GWP CH_4 at 23x CO_2

Needed Sequestration	CONV	ALT	SEM	*P*-value
Stocking density, m^{-2} $animal^{-1}$	12100	10700		
Days				
Growing				
Total CO_2e hd^{-1}, kg	1063.4	968.3	55.5	0.11
Total C $animal^{-1}$, kg	290.0	264.1	15.1	0.11
Needed sequestration, g C m^{-2}	24.0	25.1	1.3	0.39
Hectares $animal^{-1}$	0.43	0.39	0.02	0.11
Finishing				
Total CO_2e hd^{-1}, kg	1546.0	1917.0	119.0	<0.01
Total C $animal^{-1}$, kg	421.6	522.8	32.5	<0.01
Needed sequestration, g C m^{-2}	34.8	49.8	2.9	<0.01
Hectares $animal^{-1}$	0.62	0.77	0.04	<0.01

[1] Assuming C sequestered = -68 g C m^{-2} yr^{-1} from Felber et al. (2016).

Table 2.7. Carbon sequestration required when GWP CH_4 at 4x CO2

Needed Sequestration	CONV	ALT	SEM	*P*-value
Stocking density, m^{-2} animal^{-1}	12100	10500		
Days				
Growing				
Total CO_2e hd^{-1}, kg	746.3	666.6	42.1	0.07
Total C animal^{-1}, kg	203.5	181.8	11.5	0.07
Needed sequestration, g C m^{-2}	16.8	17.3	1	0.63
Hectares animal^{-1}	0.30	0.27	0.02	<0.01
Finishing				
Total CO_2e hd^{-1}, kg	1196.9	1403.7	74.3	0.02
Total C animal^{-1}, kg	326.4	382.8	20.3	0.02
Needed sequestration, g C m^{-2}	27.0	36.5	1.9	<0.01
Hectares animal^{-1}	0.48	0.56	0.03	0.01

[1] Assuming C sequestered = -68 g C m^{-2} yr^{-1} from Felber et al. (2016).

FIGURES

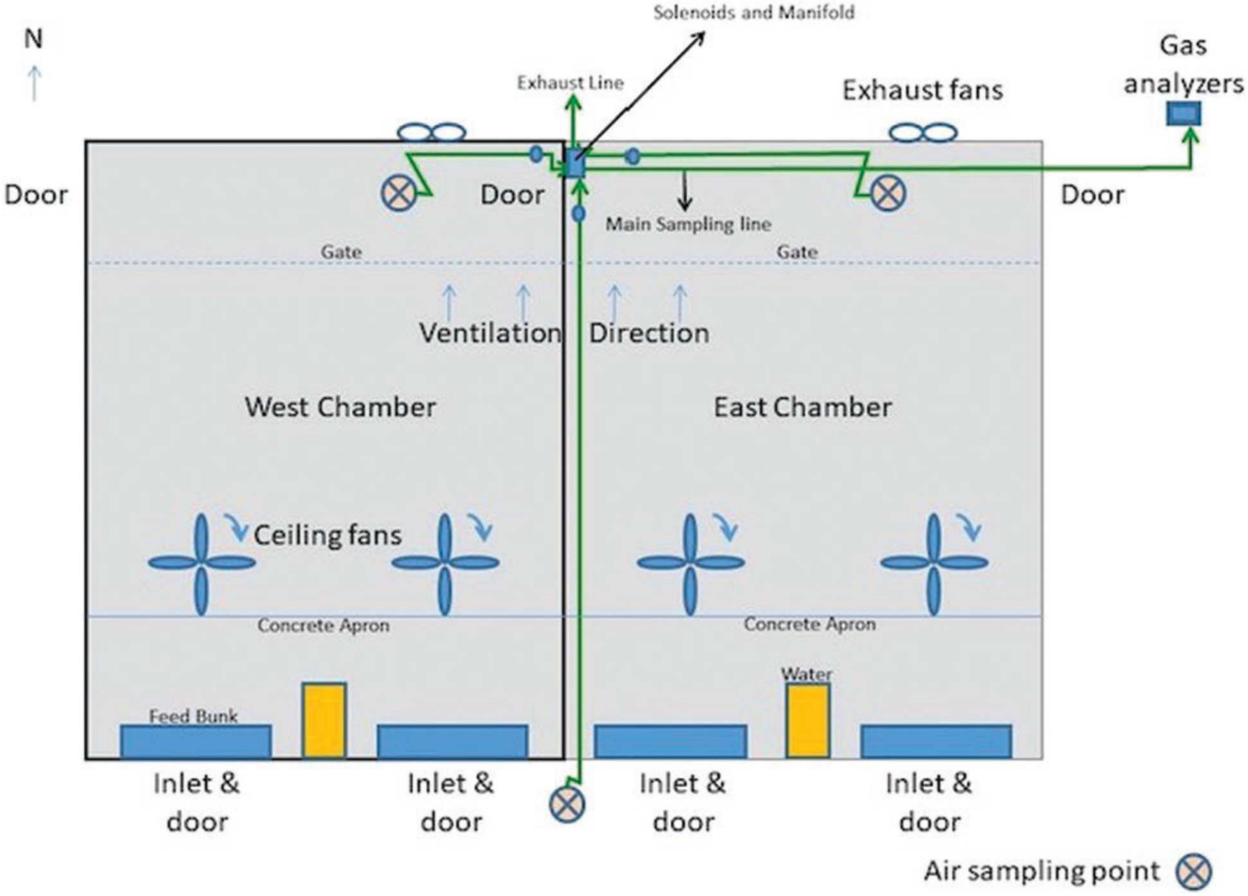


Figure 2.1. Large pen chamber layout. Side by side chamber used to measure CH_4 and CO_2 in lactating and gestating cows in ALT system and all calves during growing and finishing period post weaning

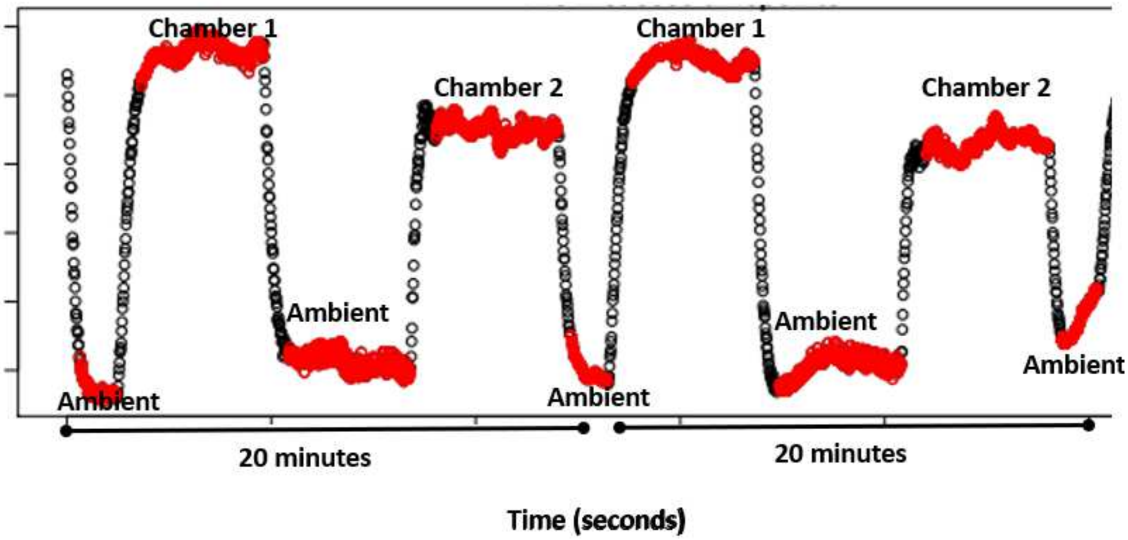


Figure 2.2. Output from statistical software (R Foundation, Indianapolis, IN) of data from large pen chamber. Data highlighted in red was used to calculate the average CH_4 and CO_2 concentrations during each chamber and ambient air samplings. Two 20-minute cycles of CH_4 are shown. The difference in mean concentration of air samplings for each side of the pen chamber was used to calculate CH_4 and CO_2 production animal^{-1} day^{-1}.

Figure 2.3. Interaction of CO_2e with treatment and diet for CO_2e from CH_4, CO_2e from CO_2, and total CO_2e assuming 23x CO_2e for GWP of CH_4.

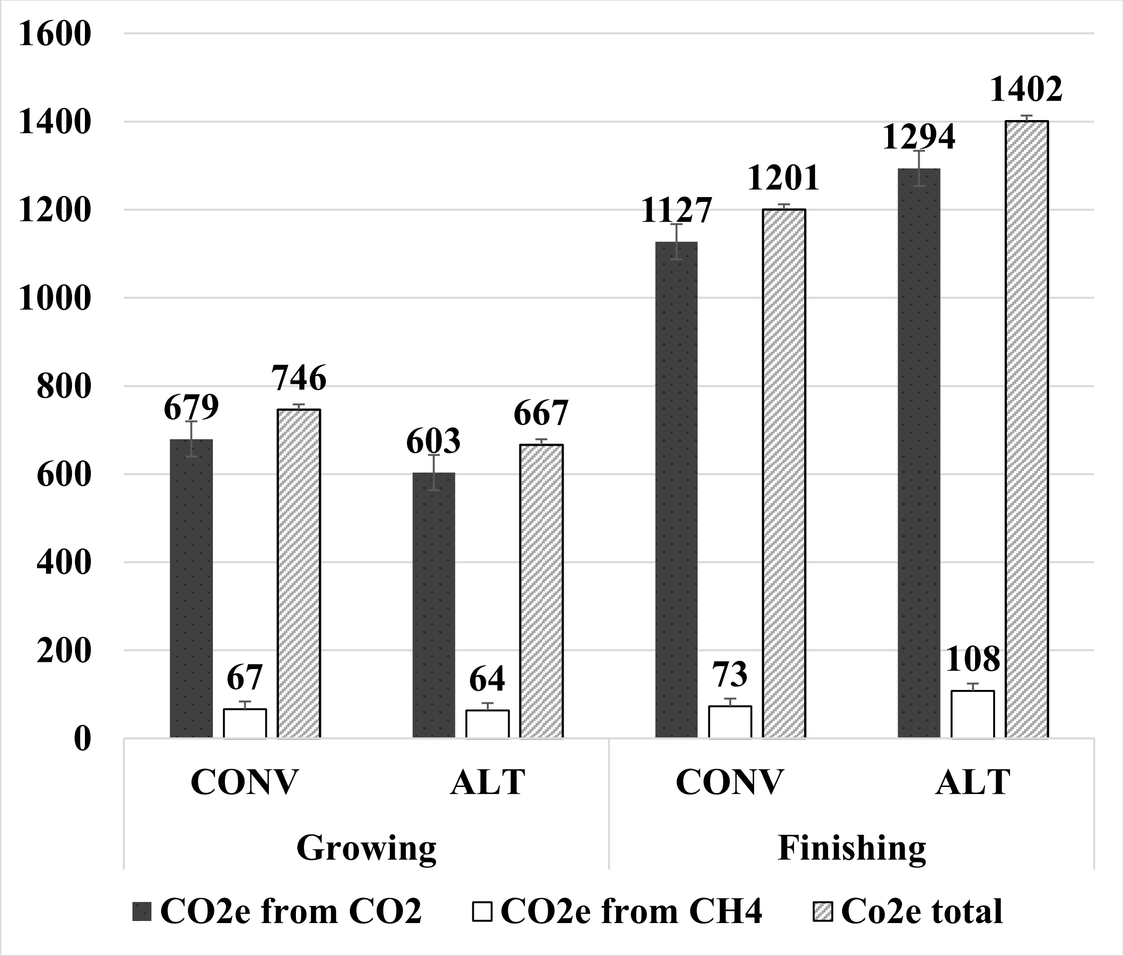
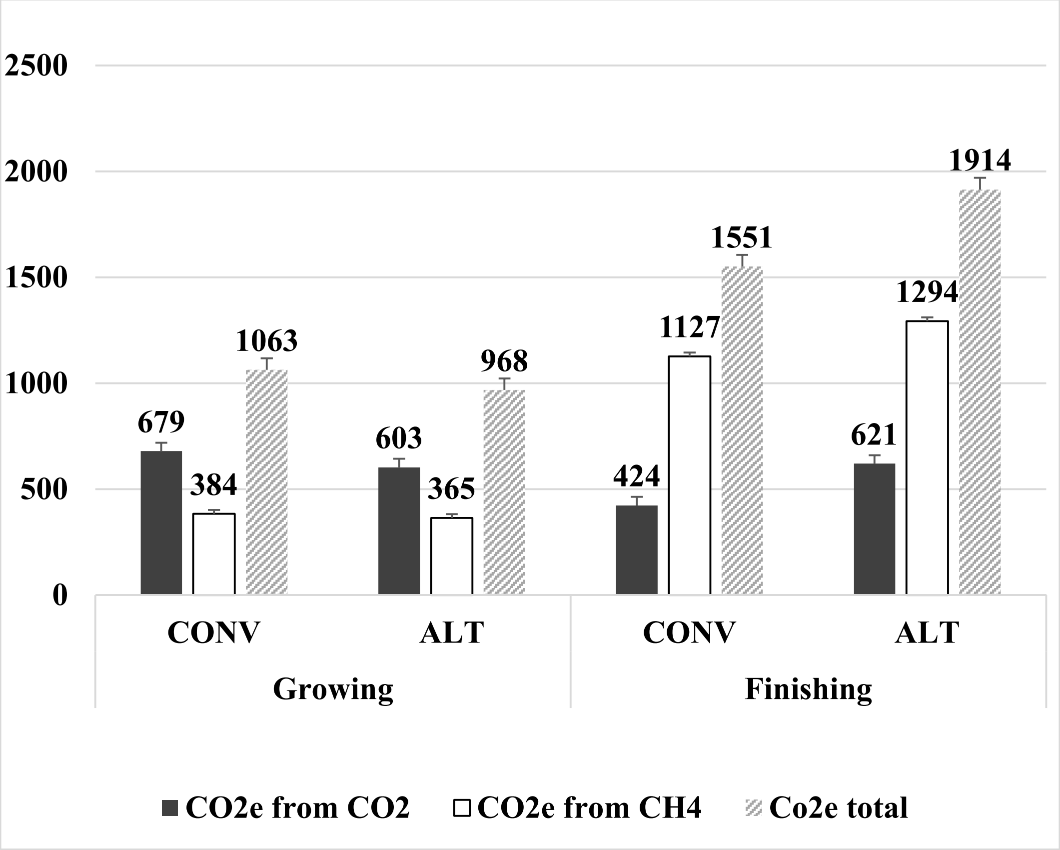


Figure 2.4. Interaction of CO_2e with treatment and diet for CO_2e from CH_4, CO_2e from CO_2, and total CO_2e assuming 4x CO_2e for GWP of CH_4.



Impact of conventional grazing or partial confinement cow-calf production on year-round greenhouse gas emission and carbon balance

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ABSTRACT

In this study, two beef production systems were examined using relatively novel applications of the traditional eddy covariance method (EC) to directly and simultaneously measure GHG production and uptake over grazed areas, using large pen chambers to measure GHG production in the confined spaces, and using new methods of GHG accounting (global temperature change potential, GTP, and GWP*) to account for both emissions and breakdown in the atmosphere of short-term pollutants such as methane (CH_4). Conventional (CONV) production was the pasture-based system with cows wintered on corn residue, with field-scale fluxes of CH_4, N_2O and CO_2 measured over brome, oat forage, and corn residue while tracking animal movements with GPS. A partial-confinement system (ALT) raised cows and calves in a drylot and grazed cover crops and corn residue over the fall and winter. Methane and CO_2 emissions measured using a large pen chamber for cow-calf pairs, and for growing and finishing calves. Calves from both production systems were grown and finished under similar conditions. Cattle from the CONV system produced more CH_4 and CO_2 but produced more beef per cow exposed (321 and 303 kg HCW for CONV and ALT, respectively). Measured CH_4 and modeled N_2O emissions totaled 7.5 ± 0.3 and 7.4 ± 0.3 kg CO_2e kg^{-1} HCW for CONV and ALT production, respectively. There was a measured uptake of 233 g C m^{-2} and 98 g C m^{-2} from the brome pasture and oat forage grazing, respectively. All CH_4,

CO_2, and N_2O emissions from gestation, lactation, growing, and finishing production stages in the CONV system were less than C sequestration when using both GWP_{100} (0.7 kg CO_2e kg^{-1} HCW C sink after subtracting emissions) and GWP* (10.9 kg CO_2e kg^{-1} HCW surplus C sink after subtracting emissions).The ALT system was a net source of C after accounting for C sequestration when using GWP_{100} (16.7 kg CO_2e kg^{-1} HCW C source after subtracting sequestration) and GWP* (7.1 kg CO_2e kg^{-1} HCW after subtracting sequestration).

Keywords: Beef cattle systems, methane, carbon dioxide, carbon sequestration

INTRODUCTION

Production of methane (CH_4), a potent greenhouse gas (GHG), from cattle has been studied in-depth since the 1990s, and research has noticeably intensified in recent decades (Coates 2017). Methane is naturally produced during enteric fermentation by ruminants, and some studies suggest that removing meat products from human diets will lead to a reduction of the global GHG production (Carlsson-Kanyama and Gonzalez 2009; Castañé and Antón 2017). However, other recent research (Place and Mitloehner 2021) has assessed new methods of GHG accounting (Allen et al., 2018, Balcombe et al., 2018, Cain et al. 2019, and Smith et al., 2018) that included calculating the breakdown of CH_4 in the atmosphere and the relative effect on global ambient temperatures. Place and Mitloehner (2021) outline new models indicating that both the beef and dairy industries can be a carbon sink and reduce GHG concentration in the atmosphere by maintaining herd size and/or taking steps to reduce daily cattle emissions. These findings challenge the predominant theory that cattle production is a major contributor to the climate change (Aydinalp and Cresser 2008).

In addition to the accounting methods, over the last 20 years, greater emphasis has been put on quantifying total GHG production of the beef production system including CH_4 from animals, N_2O from manure, and contributions from secondary emissions (Beauchemin et al., 2010 and Rotz et al. 2019). Secondary emissions include crop production and total fossil fuel use for equipment production and operation used in today's mechanized agriculture (Stackhouse-Lawson et al., 2012). Grasslands have also been identified as carbon sinks that may improve the carbon (C) footprint of beef production through C sequestration (Gourlez de la Motte et al., 2018 and Mosier et al., 2021). To measure C sequestration, sophisticated novel approaches are needed to continuously monitor GHG production over areas without affecting natural behavior and grazing patterns of livestock or wildlife. One such novel approach is a combination of inverse dispersion modeling and eddy covariance measurements.

Inverse dispersion uses gas concentration sensors downwind of animals to calculate CH_4 production using a dispersion model. In this model, cattle can be considered either point sources, or the fetch area is considered an area source of emissions (Felber et al. 2015). Point source calculations require individual animal positioning. With an area source, cattle are treated as a uniform source of GHG across a grazed area and animal positions are not needed (McGinn et al. 2015). Coates et al. (2017), Dumortier et al. (2021), Gourlez de la Motte et al. (2018), Todd et al. (2019), and Tomkins and Charmley (2015) used a variety of cattle types, GHG sensors, and flux footprint models to estimate animal methane emissions to quantify the robustness of open-path lasers. Each of these recognized area sources could be assumed, but limitations and inaccuracies could result from assuming animal grazing distribution was uniform across time.

Eddy covariance method (EC) has been used extensively since the 1980s to better understand the dynamics of C flux in different climates, ecosystems, and weather conditions. Several studies have been conducted using EC to measure the GHG fluxes of grazed lands and assuming animal grazing distribution is homogenous or random (Dengel et al., 2011). Some have used the EC technique to measure CH_4, CO_2, and N_2O flux from large cattle feeding operations (>10,000 hd; Bai et al. 2015, Prajaya and Santos, 2019). These data are an important step in understanding GHG production, but it is difficult to make conclusions of emissions animal^{-1} given the other sources of variation and GHG (roads, vehicles, manure, etc.) with no way of quantifying the relative contribution of each source.

More recent GHG measures using open-air eddy covariance techniques (Dumortier et al., 2021 and Felber et al., 2015) have attempted to quantify C balance in beef and dairy grazing systems. The EC technique simultaneously measures any CH_4 and CO_2 incorporated into the ecosystem through C sequestration and production from enteric fermentation and animal respiration. Using the flux footprint model and estimates of stocking rate in the fetch area, these studies measured net flux of CH_4 and, after accounting for CO_2 from respiration, estimated C balance during the grazing period. Gourlez de la Motte et al. (2018) and McGinn et al. (2015) measured net C uptake over the grazing season after accounting for animal C production, indicating that beef grazing systems can be a net sink of C, rather than a source. Expansive data investigating GHG production of cattle in various environments in the production cycle is needed to develop systems of beef production that maximize performance while minimizing GHG loss.

In addition to the challenges with carbon accounting and measurement approaches described above, a better understanding of the efficiency and carbon footprint of the beef production system requires the comprehensive approach examining all of its segments (cow-calf, stocker-backgrounding, and finishing) and accounting for the the interactions between the segments. There is very limited research available investigating both the performance and GHG emissions of cattle as they develop in different beef systems. Large-scale models have been developed to estimate animal life cycle GHG production (Beauchemin et al., 2010, Rotz et al., 2019, and Stackhouse-Lawson, et al., 2012), but no data exist measuring the same animals through all stages of production.

In this study, we attempt to fill the knowledge gaps by advancing the accounting and methodological approaches to quantify both GHG emissions and carbon sequestration from cattle raised in different environments over the entire production cycle. The main objective of this study is to assess and compute total GHG (CO_2, CH_4, and N_2O) emissions and uptake in two cow-calf production systems. Emissions of N_2O, CO_2, and CH_4 from each environment were analyzed to estimate total emissions and compare the quantity of emissions to C sequestration.

MATERIALS AND METHODS

Use of Animal Subjects and Experiment Site

All facilities and management procedures used in this experiment were approved by the University of Nebraska – Lincoln (UNL) Institutional Animal Care and Use

Committee (IACUC # 1491). For a complete description of treatments and materials and methods, refer to Carlson (2021). Over a 3-year period, this research was conducted at the Eastern Nebraska Research and Extension Center near Mead, NE. At the onset of the trial, multiparous crossbred beef cows (n = 160, average age 6.2 ± 2.8 years old) were blocked by age and assigned to one of 2 treatments. The conventional system (CONV) was a late-spring calving herd maintained on brome-grass pastures and maintained as dry cows on corn residue during winter months. The alternate system (ALT) was a confinement-based system where cows were maintained in the feedlot during gestation through spring and mid-summer. Cows calved late summer in the feedlot before being turned out to graze secondary annual forage from mid-fall through mid-winter. Cows in the ALT system spent the rest of the winter grazing corn residue before returning to the drylot. Before the current trial, cows originated from 2 herds of similar genetic background within the UNL beef cow-calf research system. Cows were blocked by source, age, and assigned randomly to one of two production systems with four replicates and remained in their assigned treatment for 3 years of the experiment. Replicate herd size was maintained at 20 cows by using replacements from a fifth replicate of open, multiparous cows sourced from one of the same herds as the original 160 cows. Replacements in the fifth replicate were eligible to be used once they had been maintained in their treatment system for approximately one year.

Conventional Cow-Calf System Calving, Breeding, and Weaning

The CONV herd was maintained on smooth bromegrass pasture from May 1 to October 25th but weaned on grass October 15th. Stocking rates on grass each year were 1.21 ha/cow. Pastures were fertilized with nitrogen (90 kg/ha) in the form of urea in April each year. Cows were exposed to bulls from July 12th to September 12th year 1 and July 6th to September 4th year 2. Calves from all four replicates were comingled in one pen and fence-line weaned and then sent to the ruminant nutrition feedlot at ENREC. After weaning cows were maintained on corn residue from October 26th until March 15 of the following year. From mid-March until April 30th, cows were maintained on dormant grass pasture and fed ground hay (11.3 kg DM per day) until turnout on grass pasture again. Stocking rates on corn residue were 1.69 and 1.43 ha per cow for years 1 and 2, respectively.

Alternative Cow-Calf System Calving, Breeding, and Weaning

The ALT herd was maintained in confinement pens from March 15th until October 23rd. From March 15th to the onset of calving on July 18th, cows were fed at maintenance. Cows were allowed 76 cm of bunk space and 82.7 m^2 per cow/calf pair. Diet information is presented in Table 1. Intakes were adjusted through calving to meet lactation needs. During years 1 and 2 diets consisted of 55% modified distillers grains (MDGS), 40% low-quality forage (wheat straw in year 1 and 13% wheat straw and 25.7% oat straw, and 2.66% cornstalks on average for year 2). Diets were changed in year 3 because of the lack of availability of MDGS due to ethanol plant shutdown during the COVID-19 outbreak. Cow diet in year 3 was 35% MDGS, 20% corn silage, 40% wheat straw, and 5% supplement. In the lactation phase of year 3, corn silage was replaced with corn forage silage. For one field in year 3, forage silage was part of the crop rotation that allowed for oat cover crop planted after wheat harvest. Forage silage was planted in place of wheat for one field prior to forage oats in year 3 while the other acres were wheat. This forage silage was low in starch due to little grain production

(Starch = 0.8% of DM). Cow/calf pairs grazed fall oats (*Avena sativa*) from October 23rd to January 13th year 1 and October 23rd to January 8th year 2 at stocking rates of 1.19 and 1.16 ha per cow for years 1 and 2, respectively. Breeding started in the feedlot pens and continued to oats from October 11 to December 12 year 1 and October 18 to December 17th of year 2.

Post-weaning calves from each system maintained their herd replicate during a 116-day growing and then a subsequent finishing period. Calves were fed to a common backfat thickness in the finishing period which was predicted based on fat accretion using 2 ultrasound backfat thickness measures. Average calf growth performance, feed intake and carcass characteristics were measured for each replicate within the treatment. For limit-fed cows, growing and finishing calves feed was delivered using a truck-mounted feed mixer and delivery unit with scale measurements to the nearest 0.45 kg (Roto-Mix model 414, Roto-Mix, Dodge City, KS). During the finishing phase ALT cattle were on feed for 154 and 196 d (first and second shipping dates, respectively; year 1), for a weighted average of 174 d. The CONV cattle were on feed for 145 and 173 d (first and second shipping dates, respectively; year 1), with a weighted average of 156 d. In year 2, ALT cattle were on feed for 154 and 210 d (first and second shipping dates, respectively), with a weighted average of 161 d. In year 2, TRAD cattle were on feed for 120 and 155 d (first and second shipping dates, respectively), with a weighted average of 125. For a detailed description of the measurement of forage quality in the brome pasture and oat forage, refer to the Appendix. A more detailed description of diets, post-weaning calf performance, and CH_4 and CO_2 production can be found in Carlson (2021) and McPhillips (2021).

Greenhouse gas monitoring

Methane (CH_4) and carbon dioxide (CO_2) production were estimated at each stage of production and each scenario across both systems. The yearly cycle of GHG emission measurements for both systems is shown in Figure 3. Cows in the ALT system cycled through a pen-chamber to measure CH_4 and CO_2 (Figure 1.1) at 8 months gestation and between 15 and 60 days post-calving during the lactation period while in confinement.

To measure GHG, a large pen-scale chamber was used that measured CH_4 and CO_2 by the difference in incoming and outgoing air concentrations of CO_2 and CH_4. For a full description of the pen chamber technique, refer to Winders et al. (2020). Each chamber was 15.2 m x 13.3 m and animals access feed and water from 2 feed bunks and 1 automatic water tank (Watermaster 54, Ritchie Industries, Inc. Conrad, IA) per chamber. Air is pulled through each pen through inlets above the feed bunks and exits through the fans, with a sampling line positioned above the fans. Fans were calibrated twice, once prior and once after the trials (FANS System, Iowa State University). The airflow rate through the chambers with two fans running was 1,274 L/s. Gases were analyzed using an LI-7700 CH_4 analyzer and an LI-7500DS CO_2 analyzer (both LI-COR Biosciences, Lincoln, NE). The methane analyzer operates using near-infrared laser and wavelength modulation spectrometry to detect the absorption of CH_4 in the air sample. The resolution of this instrument is 5 ppb at 10 Hz, in typical ambient concentrations (2 ppm CH_4). The CO_2 analyzer uses nondispersive infrared spectroscopy to measure CO_2 and water densities in the air sample. Data from both analyzers were captured at 1 Hz. The exact start of each 20-minute interval occurred at the start of the 2-minute ambient air sampling. The start of the first 20-minute interval was determined for each day's data based on the change in air concentrations. The air sampling system cycled between 3 sampling lines: one line in each chamber (east and west) and one line on the south side for the ambient air concentration. Air was sampled in each pen using a sampling line with a pump and controlled with a solenoid system and a data logger. Before cycling through the sampling of the two pens and ambient air, an additional ambient air sample was collected for 2 min to complete a 20-min cycle. Solenoids switch sampling between the ambient line, east pen, and west pen, allowing for each pen to be sampled for 6 min. A 2-min ambient sampling allows for easy recognition of when the cycle resets when data were being analyzed as pen 1 always follows the 2-min sampling period. An adequate time of 6 min allowed for the system to be flushed between pen 1 and pen 2 sampling periods and provide ambient concentrations of CO_2 and CH_4. Emissions data were averaged across each 6-min time point, excluding the first 60 s to avoid including lower measurements as gas acclimates solenoid switching. Gas production per day was an average of all 6-min measurements per pen for a 24-h feeding period. Data before the start were removed (between 0 and 19 min per day) then using high throughput software (R Foundation, Indianapolis, IN) which calculated the mean concentration of CH_4 and CO_2 during each source sampling within every 20-minute cycle. An illustration of air concentrations in each chamber in a 20-minute cycle is shown in Figure 1.2. From these data, the mean concentration of CH_4 and CO_2 throughout the day was calculated. Data were further processed so that the 24-hour period from feeding to feeding was considered a day. Animals were fed from the same load of feed to cows in the open-lot pens. Feeding times were recorded by feeding software in the feed delivery truck.

Each replicate of cows in the ALT system was in the pen chamber system for 5 days during gestation and lactation. During gestation, cows were split evenly between both chambers of the barn. During lactation measurements, cows and calves were paired up so that each side of the chamber housed half of the cows with their respective calves. After 5 days, animals were removed, and the manure that accumulated over the previous 5 days was monitored for GHG emissions for 24 hours. On the 7th day, manure was removed from the barn using a skid loader, and then a final 24-hour measurement of the empty barn with no manure or cattle was performed for baseline measurements. The GHG production from manure was calculated by the difference from baseline. It was assumed that the GHG contributions from manure were equal to one-half of what was measured during the 24 hours, since, on average, half of the accumulated manure was present in the barn at any one time during the 5-day measurement period. The GHG contribution from manure was subtracted from the total GHG emissions to determine GHG emissions from the cattle. This correction was small, averaging 1.32 g of CH_4 and 130 g of CO_2 per animal per day. When the 7-day cycle was complete, the cycle was repeated for the other 3 reps in the production system. Ammonia concentration was a concern during monitoring during lactation. It was repeatedly noted that ammonia concentration would increase incrementally over the 5 days of measurements from 2 ppm up to 25 ppm. There is no evidence that this ammonia build-up affected CH_4 or CO_2 values during measurement. As a result, during year 3 of the study cows and calves were in the barn for 4 days and manure was measured for days 5 and 6 before being cleaned the start of day 7.

Calf CH_4 and CO_2 Contribution Estimation

Flux from cow/calf pairs was measured in the entire system. However, since cow and calf emissions would be dramatically different, an estimate of calf emissions was needed to partition the total between the cow and a calf. During year 3 of pen measurements, cows were removed on day 5 but calves remained in the barn for an additional 6 hours. During this period, CH_4 and CO_2 production from the calves was measured. After the 6 hours, calves were returned to the cows. The remaining times of days 5 and 6 were monitored for manure CH_4 and CO_2 and then the barn was cleaned on day 7. During this period there was about 0.3 kg DM per calf of feed in each feed bunk, but no measurable feed consumption was observed over the 6 h. Thus, emissions are expressed only per calf per day and not per unit of feed intake. The same calves post-weaning were put in the pen chamber during the growing phase. All of these daily CO_2 and CH_4 values were used to estimate the relationship between these gases and growth. Calf emissions, in combination with data from the post-weaning growing period, would be the foundation for estimating the calf contribution of CH_4 and CO_2 in not only the ALT system, but the open-air measurements on the CONV herd as well.

Eddy Covariance Technique

The measurement of CH_4 and CO_2 flux was used to measure GHG production from herds in grazed scenarios. One unique challenge was the crop rotations required different fields for measurement of corn residue and forage oat grazing. Two trailers were constructed to move all GHG monitoring equipment from field to field. These two trailer units allowed GHG monitoring to occur simultaneously especially in late fall and early winter months when CONV cows were grazing on the corn residue, while ALT cows were grazing on the oat forage.

Underground power lines were installed to provide power to the bromegrass pasture site, the corn residue field, and the third field for forage oat grazing. In some areas, permanent power installation was not possible, so a generator (Perkins 8.5 kW diesel generator) was installed on one of the trailers to supply power to all equipment. Foam insulated enclosures were constructed to shield GHG analyzers from extreme cold and heat and a mini-split A/C and heater was installed to maintain temperatures in the enclosures.

To measure CO_2 production, an open path laser was used (LI-7500DS; LI-COR Biosciences, Lincoln, NE). For N_2O and CH_4 a closed-path analyzer was also installed (N2OM1-913, Los Gatos Research San Jose, CA).

Flux footprint Models

To estimate the area from which the GHG fluxes were generated, the Kljun footprint model (Kljun et al., 2015) was used. This model depends on half-hourly values of the variables below:

Abbreviation Units	**Variable and Description**	**Units**
H	Sensible heat flux	[W m^{-1}]
u*	Friction velocity	[m s^{-1}]
u	Mean wind speed at zm	[m s^{-1}]

wind dir	Wind direction in degrees (of 360) for rotation of the flux footprint	Degrees [°]
Ta	Air Temperature	[K]
ρv	Air density	[kg m^{-3}]
P	Air Pressure	[kPa]
sig v	standard deviation of lateral velocity fluctuations	[ms$^{\square 1}$]
meas hgt BL	Planetary Boundary Height	[m]
h	Canopy Height	[m]
z_m	Measurement height	[m]
z_o	Roughness length (=0.15 * h)	[m]

Flux footprint Model after Kljun et al. (2015)

The Kljun model utilizes planetary boundary height available from Copernicus Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form) while other data are available for the flux station .

$$f(x,y) = (2\pi)^{-0.5}\left(a_c {b_c}^{0.5} Ax_r(1 + c_c Ax_r)^{-0.5}\right)^{-1} \exp\left(-0.5{y_r}^2\left(a_c {b_c}^{0.5} Ax_r(1 + c_c Ax_r)^{-0.5}\right)^{-2}\right) \times 1.4524A(Ax_r - 0.1359)^{-1.9914}\, exp\left(\frac{-1.4622}{Ax_r - 0.1359}\right)$$

Therefore, simplified the above equation we have the equation below which can be utilized to calculate the footprint distribution for each animal.

$$f(x,y) = 0.207244A(Ax_r - 0.1359)^{-1.9914}(ABx_r)^{-1}(1 + 20.0Ax_r)^{0.5} \exp\left(-\frac{1.4622}{Ax_r - 0.1359}\right) \exp\left(-0.063965{y_r}^2\,(ABx_r)^{-2}(1 + 20.0Ax_r\,)\right)$$

GPS Monitoring

To track individual animal movements, global positioning system (GPS) loggers i-gotU GT-600 (Tenergy®, City, State) were given to each cow, bull, and calf in one rep of each system. These provided the necessary information to develop a precise model to calculate CO_2 and CH_4 flux during grazing. The loggers were powered by 3.7 Volt Lithium-Ion Batteries (15600mAH) that are rechargeable and have circuit board protection. The i-gotU loggers are turned on and inserted into a square plastic protective casing. The casing is wrapped with duct tape for color identification, sealing and protecting, the GPS logger from the elements. The casings were securely fastened with bolts to a polymer collar or leather collar. The collar is then placed around the neck. Collars are checked for proper fit for each animal so normal grazing tendencies are not compromised.

Some technical problems resulted in a lack of GPS data including: 1) battery life- battery dies during the time spent on the animal, 2) battery does not charge fully or did not charge at all. 3) record timing- the sensors were programmed to record animal locations every 10 minutes. However, there were instances when data were intermittent over variable durations. Given limitations in battery life, GPS collars were removed every 4 to 6 weeks, data were downloaded, and batteries were recharged before placing the data logger back on each animal. It required a minimum of 7 days between taking collars off, downloading, recharging, and putting collars back on the animals which caused some gaps in the data. Eddy covariance fluxes were not used when GPS units were not on the animals.

Calculating the spatial distribution of the Livestock

The spatial distribution of the livestock was averaged over a 30-minute duration and constrained between the minimum and maximum latitudes as well as maximum and minimum longitudes. If a data point was not recorded in a given 30-minute window, that was considered a missing data point. A gap-filling procedure was used to calculate the likely location of the animal based on the previous and subsequent GPS coordinate. The proportion of missing data before and after gap filling for different campaigns is shown in Table 3. Using the gap-filled data, animal distribution is illustrated using pixel color to reflect the density of animal occupancy over a period of time (Figure 6). While there are GPS coordinate data spread throughout the pasture, notable patterns emerge. When grazing a brome pasture, cows, calves, and bulls traveled fences more often, spent more time at the water tank, and spent time around a tree for shade during warm temperatures. When grazing oat forage, animals found a depression in the topography of the grazed field to get shelter from the wind and spent more time at the water tank. The oat forage field was the only instance when the EC tower was located at the north end of the field and not in the center. Oat forage was susceptible to trampling so animals were given access to the south half before being moved to the north half, however, the EC tower remained in the center of the north and south paddocks.

Rotating Animal Locations based on wind direction

The GPS latitude and longitude values were converted to x and y coordinates with the tower as the reference or origin point; (x, y) = (0,0) point. The North winds have a 0 or 360° designation while the south winds are designated 180°. Each animal has an x and y coordinate that needs to be rotated counter-clockwise and given new (rotated) coordinates (x_r,y_r). Rotated coordinates are then put in the flux footprint equations to determine the contribution of each animal to the flux (Figure 7).

$$r_1{}^2 = x_1{}^2 + y_1{}^2$$

$$\theta_1 = \arctan\left(\frac{y_1}{x_1}\right)$$

If $\theta_1 < 0 \; then \; \theta_1 = \theta_1 + 360$

If $y_1, x_1 < 0 \; then \; \theta_1 = \theta_1 + 180$

If $y_1 = x_1 = 0 \; then \; \theta_1 = 0$

$$r_1{}^2 = x_1{}^2 + y_1{}^2 = x_{1r}{}^2 + y_{1r}{}^2$$

$$y_{1r} = (x_1{}^2 + y_1{}^2)^{\frac{1}{2}} \sin(\theta_1 - \Theta)$$

$$x_{1r} = (x_1{}^2 + y_1{}^2)^{\frac{1}{2}} \cos(\theta_1 - \Theta)$$

When x_{1r} is negative, it means the animal is located downwind of the tower and does not contribute to the flux. The values of x_{1r} and y_{1r} may be input to the flux footprint equations to estimate flux contribution from Animal 1.

Determining Animal Emissions

The flux of CH_4 measured by the eddy covariance system is related to the number of animals upwind of the sensors and their location in the flux footprint using the following technique. From Chopra et al. (2019), the methane flux measured at an EC tower (F_{CH4}, µmol m^{-2} s^{-1}) is the product of a) the footprint contribution (ω, m^{-2}) for the given location of a methane cylinder for a particular orientation of the footprint for a particular half-hour and b) the known flow rate of methane (Θ_{cyl}, µmol s^{-1} or g CH_4 s^{-1}) being released from the cylinder upwind of the EC tower. This is expressed as,

$$FCH4 = \omega * \quad \mathrm{cyl}$$

$$F_{CH4} = \omega * \Theta_{cyl}$$

where pure CH_4 gas was flowing continuously at a constant rate for the 30-minute flux measurement period and ω was the footprint contribution at the point where the cylinder was located for a footprint for the same 30 minutes (i.e., the contribution per cylinder). In quantifying methane emissions from cattle, we assume a) each animal represents a gas cylinder and b) there is a small background methane flux (F_{mb}) if no animals were present in the footprint so the total measured half-hour methane eddy covariance flux would be,

$$F_{CH4} = \omega * \Theta + F_{mb}$$

This is the flux that would be measured if one animal were upwind of the eddy covariance tower and emitting methane at a rate of Θ. If we consider daytime hours when methane fluxes are more reliable due to surface heating generating sufficient turbulence, for a particular half-hour, we have *n* number of cattle in the footprint (given its size and orientation that half-hour). Each of these animals is emitting CH_4 so the total CH_4 that would be measured at the EC tower would be the simple sum of the product of each cow (designated by subscript i) at its respective location in the footprint and corresponding footprint contribution,

$$FCH4 \quad = \sum_{i=20}^{n} \mathrm{F}_{CH4i} = \sum_{i=20}^{n} \omega_i \;\; _i \; + \mathrm{F}_{mb}$$

where values are summed over *n* animals in the footprint. We assume each animal is emitting the same amount of methane so Θ_i is constant and may be removed from the summation,

$$FCH4 = \sum_{i=20}^{n} \omega_i + F_{mb}$$

This is a half-hourly flux. Our flux footprint calculations generate $\Sigma\omega_i$ from all the animals in a footprint on a half-hourly basis (for a particular footprint as determined by the wind direction and atmospheric stability). There may be random noise in the half-hourly fluxes so it is beneficial to sum the fluxes over the daytime hours which will tend to cancel some of the noise inherent in these measurements. The equation can be rewritten as follows,

$$Daytime\ \mathbf{FCH4} = \sum_{i=20}^{n} F_{CH4} = \sum_{i=20}^{n} \omega_i + \sum_{i=20}^{n} F_{mb}$$

where m daytime hours have been summed. The daytime methane flux and the daytime sum of the footprint contributions ($\Sigma\Sigma\omega_i$) from all the animals in the footprint that day have been calculated. If daytime $\mathbf{F}_{CH4}$ is plotted on the y-axis and $\Sigma\Sigma\omega_i$ on the x-axis for multiple days, the slope should be Θ or the average methane emission for each animal for the number of days included in the figure.

If calves and cows are assumed to produce the same amount of methane, this will greatly reduce the amount of methane per animal (considering all cows and calves as animals). However, cows and calves have dramatically different intakes and therefore different contributions to the methane flux. Calf methane contribution to the flux is calculated as follows. If each calf is assumed to be emitting the same amount of methane and that amount is allowed to increase during a period based on their estimated body mass, a half-hourly flux measured by one cow (subscript cow) and one calf (subscript calf) would be,

$$\mathrm{F}_{CH4} = \omega_{cow} * {}_{cow} + \omega_{calf} * {}_{calf} + \mathrm{F}_{mb}$$

Following the previous steps/assumptions, the daytime flux is calculated as,

$$\text{Daytime } \mathrm{F}_{CH4} = {}_{cow} * \sum \quad \omega_{cow} + {}_{calf} \sum \quad \omega_{calf} + \sum \quad + \mathrm{F}_{mb}$$

Or rewriting the equation,

$$\text{Daytime } \mathrm{F}_{CH4} - {}_{calf} \sum \quad \omega_{calf} = {}_{cow} \sum \quad \omega_{cow} + \sum \quad \mathrm{F}_{mb}$$

where Θ_{calf} is allowed to increase during the growing season as the calf weight increases.

Both of $\Sigma\Sigma\omega_{\mathrm{icow}}$ and $\Theta_{\mathrm{calf}}\Sigma\Sigma\omega_{\mathrm{icalf}}$ are calculated on a daily basis and measured daytime $\mathbf{F}_{\mathrm{CH4}}$ is calculated. A regression is fitted for a given period such that the slope is Θ_{cow}, the average emission per animal^{-1} day^{-1} during the period is included in the regression. Regression periods may be chosen to detect differences due to forage quality for example as the cattle are rotated to different pastures or forage nutrient profiles. The calculation of the CH_4 flux described above was repeated for CO_2 and N_2O. Background fluxes of CH_4 and N_2O were minimal due to low production by the environment. Greater background fluxes of CO_2 occurred from biomass sequestration and respiration of CO_2. Cattle were rotationally grazed on the brome pasture and oat forage sites, and the background flux of

CO_2 was greater in grazed areas because of biomass removal during grazing. Only fluxes from grazed areas were used to calculate background flux, and fluxes from non-grazed areas were not considered.

Allocated/weighted Calculation of Methane Flux

If the amount of methane that an animal emits on average is known as well as the flux footprint factor for the source location at the time of release, the expected methane flux can be calculated. For every liter of methane gas that an animal produces it can be multiplied by the factor of 770.682 to obtain the release rate per second in units: $\frac{\mu mol}{s}$. This is derived systematically as explained below.

L/min = $\frac{L}{min} * \frac{0.001m^3}{L} * \frac{1\,min}{60\,sec} = 1.667 * 10^{-5}\ m^3 s^{-1}$

The contribution flux that resulted from the above description was expressed as g methane animal^{-1} day^{-1}. All EC sensors do not identify the location of the source of CO_2 or CH_4. Whenever a calf was in the flux footprint of the tower, the CO_2 and CH_4 values were assumed to be equal to predicted values based on calf BW. The remaining portion of flux was attributed to only the cow. The calf contribution was calculated from BW using the depictions above. As calf weight increased, calves had an increasing proportion of the CO_2 and CH_4 per cow/calf pair. Herd daily average calf BW values were assigned by day to subtract a given amount of CO_2 and CH_4 from each cow/calf pair when cows and calves were in the footprint. Total C accumulation (sequestration) was calculated per unit area (m^2) when considering fluxes when no cattle were in the footprint. This was considered the background CO_2 and CH_4 flux. This was used to calculate the actual C balance of the herd replicate after calculating total CO_2e from CH_4 and CO_2.

During years 1 and 2 of the study, limited data were available from the EC station when GPS data were acceptable. Power outages (i.e. generator failure) and N_2O/CH_4 gas analyzer technical difficulties caused gaps in the data, especially in the first 2 years of data collection. As a result, select grazing periods from late in year 2 and most of year 3 are presented. Cows in the ALT system were put in the pen chamber system in years 1, 2, and 3. Data from growing and finishing phases in years 1 and 2 are presented. The means of DMI, CH_4, and CO_2 production are used in all GHG calculations for ALT cows. Production of CO_2 and CH_4 per unit of DMI was used to calculate daily flux for growing and finishing period GHG emissions and when ALT cows were in the pen chamber. Daily values of CO_2 and CH_4 from grazed scenarios were used to calculate emissions because DMI was not measured. To see the full scope of GHG measurement data on the 2 systems in a calendar year, refer to Figure 1.

Global Warming Potential

Studies suggest that the atmospheric life of CH_4 is 9 to 12 years while CO_2 may remain in the atmosphere for up to one thousand years (Allen et al. 2018; Thompson and Rowntree 2020). The most recent IPCC report (IPCC 2021) states that GWP_{100} overestimates the contribution of CH_4 because it fails to account for the degradation of CH_4 in the atmosphere. The new metric, GWP*, uses an equation to calculate GWP (Allen et al., 2018) based on time horizon and previous emissions. Balcomb et al. (2018) described GTP (Global temperature change potential), which is similar to GWP, of CH_4 100 year time horizon as 4 instead of 23. To test these new metrics, the estimated CO_2e from CH_4 will be presented both using 4 and 23 for the multiplication factor (IPCC 2013) to see if GWP_{100} and GTP produce different outcomes. Biogenic CO_2, while not considered a source of GHG, does contribute to CO_2 levels in the atmosphere and the carbon cycle. In this paper, all sources of C are considered an emission since all CO_2 can be and is incorporated into growing biomass. The balance of beef production will be calculated based on the difference of sequestration after subtracting all emissions (CH_4, CO_2, N_2O). Fluxes of N_2O were measured in bromegrass pasture, oat forage, and corn residue grazing. The pen chamber was not equipped with N_2O sensors. No N_2O emission data were captured from any confinement scenario (drylot cows, growing and finishing calves). To account for these emissions that were not measured, estimates from Beauchemin et al. (2010) were used to calculate N_2O, CO2, and CH4 from manure and the burning of fossil fuels.

RESULTS AND DISCUSSION

Grazing distribution

The grazing distribution is shown in Figure 6. Cattle grazing oat forage (A) had access to the south paddock from 10/28/20 to 11/27/20 and grazed the north half from 11/28/20 to 12/28/20. During A cattle grazed the entire paddock until almost all biomass had been removed. During bromegrass grazing (B) cattle were rotated between the SW and NE paddocks shown (07/17/20 to 8/20/20). Other periods in the grazing period (5/1/20 to 10/26/20), cattle grazed the SE paddock in addition to the 2 paddocks shown. In general, grass accumulation was more rapid than grazing, and cattle were rotated between pastures every 21 to 28 days. When cows grazed corn residue (C) the entire field was available for grazing. Low elevations in the field are shown in 2 concentrations in the western half. The concentration in the eastern half was the location of the mineral feeder. All three of these distributions indicate that cattle distribution over time is spread over the entire grazing area but is not homogenous. As a result, cattle are treated as point sources of CH_4 rather than the pasture as an area source. Dumortier et al. (2021) illustrated patterns in GPS location data across time for the purpose of determining animal positions relative to fetch area using 19 cows and calves in a 4.2 ha pasture. Dumortier et al. (2021) and Gourlez de la Motte et al. (2018) used the same site and cattle over different years. The pasture used was smaller than the bromegrass grazing in the present study, but similar animals and setup were implemented. Patterns in GPS data indicated that grazing distribution was not homogenous, and animals must be used as point sources (Dumortier et al. 2021). Non-uniform grazing patterns are greatly influenced by tree cover, topography, and shade (Schieltz et al. 2017). All areas used in the present study (brome pasture, oat forage, and corn residue) were relatively flat and free of landmarks and trees which likely made grazing more uniform. The flat, uniform areas were also ideal for collecting EC data.

Methane

Confined-cow

The summary of GPS, CH_4, and CO_2 production from EC in grazing scenarios is summarized in Table 3. Across years 1 through 3, the CH_4 production by ALT cows fed in confinement during gestation averaged 137 g animal^{-1} d^{-1}, and 1.8 Mcal of GE lost as CH_4 (5.9% of total GE intake). During lactation cows produced 175 g CH_4 animal^{-1} d^{-1} and 2.3 Mcal of GE lost as CH_4 (5.7% total GE intake). Diurnal variation in CH_4 concentration in the pen chamber relative to the time of feeding is shown in Figure 8. Based on frequent observations, cows fed in the drylot consistently consumed all their feed within a matter of hours. A surge in CH_4 at feeding for the first five to six hours is shown in Figure 8. A larger flux is seen in the lactation diet since DMI was, on average, 6.9 and 9.1 kg during gestation and lactation, respectively. Methane concentrations in the chamber would decrease over time until the next feeding. Patterns from the calves consuming growing and finishing diets *ad libitum* show more constant production over time due to constant access to feed. Daily production of CH_4 was similar to Chung et al. (2013) who fed alfalfa to beef cows during gestation and lactation. Methane was lower in Chung et al. (2013) at 108 g animal^{-1} day^{-1}. However, CH_4 values for Chung et al. (2013) are similar to estimated median values from NASEM (2016) model based on intake and forage quality (147.6 and 157.3 g animal^{-1} day-^{1} for gestation and lactation, respectively). Greater CH_4 production for cows in the current study is likely due to low-quality roughage (wheat straw) relative to Chung et al. (2013).

Corn residue

Values from the regression of flux from animals in the tower footprint are presented with their 95% confidence intervals. Methane production during corn residue grazing was 192.8 (± 25.9) g animal^{-1} d^{-1}. Na et al. (2013) measured dairy cows consuming diets that were 40% baled corn stalks and 60% concentrate using the SF6 tracer technique. Cows consumed 11.7 kg DM and produced 233 g CH_4 animal^{-1} day^{-1}. Feed intake on cows grazing corn residue is difficult to measure. Assuming an intake of 11.3 kg DM, the mean CH_4 production according to the NASEM (2016) model is 259 g animal^{-1} d^{-1}. This model assumes the consumption of baled corn residue, which is of lower quality than what is grazed. Cattle are selective grazers when utilizing corn residue. Leaf and husk account for 65 – 72% of utilized residue (Fernandez-Rivera and Klopfenstein, 1989). Corn residue on average is 11.2, 9.1, 40.7, 39.0 % DM grain, cobs, stalks, and husks-leaves (Lamm and Ward, 1981). In vitro dry matter digestibility (IVDMD) is 67, 47, 45, and 35% for husk, leaf, stem, and cob for grain, husks, leaf blades, stems, and cobs (Wilson et al., 2004). Typically, cows select the highest quality plant parts (leaf and husk) which are greater in digestibility. Baling residues collects all stalk and stem and these are consumed with ground residue, likely resulting in greater CH_4 production than what was observed in this study. The methane data from the current study is supported by the theory that cattle graze higher quality plant parts first. These CO_2 and CH_4 values were used for the period of October 27th to March 15th for CONV cows and January 15th to March 15th for ALT cows in all subsequent calculations.

Pasture

Methane values from cows grazing bromegrass pastures were variable over the 3 periods in the summer/fall of 2020. Early, mid, and late-season coefficients for cow daily methane were 300.46 (± 50.6), 353.6 (±107.7), and 237.9 (±56.9) during early, mid and late season. Cattle are assumed to be the only source of CH_4. Soil methanotrophy was captured in the background CH_4 flux when cattle were not in the footprint. Le Mer and Roger (2001) measured soil methanotrophy as 6.5 g CH_4 $ha^{-1}d^{-1}$ for grassland. Felber et al. (2015) used EC to measure GHG from dairy cattle and measured CH_4 to be between 400 and 448 g $animal^{-1}d^{-1}$. Pinares-Patino et al. (2007) measured CH_4 by Friesen heifers (BW = 455 kg) at grazing native grasses Holstein 1.1 or 2.2 livestock unit (LU) per acre. Production of CH_4 ranged from 162.7 to 229.2 g $animal^{-1}$ d^{-1} and DMI measured from biomass sampling was, on average, 9.4 kg daily. Dumortier et al. (2021) measured 220 g CH_4 $animal^{-1}$ day^{-1} from Belgian Blue cows grazing 9.5 kg DMI of white clover and perennial ryegrass. Late in the grazing period calf grazing and feed intake increases with subsequent decreases in milk intake. After 40 days post-partum, milk yield decreases linearly, and forage DMI increases linearly (Tedeschi and Fox 2009). From September 2nd, 2020 to October 2nd, 2020 calf age was 131 to 161 days of age. According to Tedeschi and Fox (2009), daily calf milk and dry forage intake would be approximately 5 and 4 kg, respectively during that time. Forage intake would continue to increase until weaning and cow nutrient requirements would decrease, thereby decreasing intake and CH_4 production. Cool-season grasses have greater protein and lower neutral detergent fiber (NDF) values early and late in the growing season, and grass protein and quality are lowest mid-summer (Abdalla et al., 1988, Smart et al., 2006). However, in the current study IVOMD and CP did not change (Table 2) over the grazing period because the coefficient describing IVOMD and CP values over time was not different from zero. (Figure 7). Therefore, differences in CH_4 production were likely due to changes in intake rather than diet quality during this summer pasture grazing period because decreases in CP and IVOMD were not observed in diet samples.

Oat forage

Methane production from forage oat grazing was estimated as 364 g per pair^{-1} d^{-1} (309.23 (±43.1) cow and 54.6 g per calf. Forage oat in vitro organic matter digestibility (IVOMD) and crude protein (CP) content did decrease over time. Since all data during this period are pooled together for the regression, it is unclear if changes in CH_4 production occurred over the grazing period as diet CP and IVOMD declined. Oat forage quality was greater than bromegrass based on IVOMD (51.8 and 57.6, brome and oat, respectively) but not CP (10.4 and 7.8 for brome and oat, respectively). Greater CH_4 production per day in oat forage may be explained by increased intake. While overall

CH_4 production per pair was numerically greater in oat forage (364 ± 43 g) than bromegrass (349.6 ± 54), the greater CH_4 was driven by greater intake since forage quality was greater and CH_4 production per unit of intake should be lower in oat forage relative to brome pasture. Maxin et al. (2020) measured *in vitro* CH_4 production and digestibility of seven plant species used for cover crops. Digestibility was 76 to 91% and 1.03 to 1.47 mmol g^{-1} DM. Based on *in vitro* CH_4 cover crops could produce 382 to 546 g CH_4 $animal^{-1}$ day^{-1}. Additional comparisons cannot be made because no other studies were found measuring CH_4 production of ruminants grazing annual cover crops.

Calf CO_2 and CH_4

Production of CH_4 and CO_2 from cows and calves across both systems is shown in Table 5. Calf production of CH_4 and CO_2 during the 6 h measurement of ALT calves was 16.5 and 1468 g $animal^{-1}$ d^{-1}, respectively. Modeled calf weights during the time of measurement were 91.8 kg. Limited research is available on calf CO_2 and CH_4 production pre-weaning. Stackhouse et al. (2011) used Holstein bottle-fed calves (BW = 54 kg) and Holstein calves fed starter-feed (BW = 159 kg) and measured CO_2 and CH_4 production over 24 h periods using a pen scale measurement that could hold 3 animals at a time. Stackhouse et al. (2011) measured 0 g CH_4 and 1391 g CO_2 shortly after birth (54 kg BW). Holstein calves at 6 weeks of age produced 47 g CH_4 and 5411 g CO_2. Ramirez-Restrapo et al. (2015) used SF_6 tracer method and indirect respiration calorimeters to repeatedly measure CH_4 from Holstein heifers. Average heifer BW during measurements were 151, 182, 196, 216 kg for respiration calorimeter and 92, 148, 159, and 183 kg for the SF_6 tracer method. These are the only data sets we are aware of for CO_2 and CH_4 production of small calves. Data from these 2 studies were combined with measured values of calves from the ALT system both pre and post-weaning (Table 4). Regression of CH_4 and CO_2 are shown in Figure 4. The equations from the calf contribution were used to estimate calf GHG production in both ALT and TRAD systems of calves during all extensive grazing measurements of cow-calf pairs.

CH_4 production per day, g = 0.0013(BW, kg)^2 + 0.2787(BW, kg) -17.738 $R^2 = 0.95$

CO_2 production per day, g = 0.0309(BW)^2 + 12.387(BW, kg) – 260.77 $R^2 = 0.82$

Based on our measured values of CO_2 and CH_4 in small calves, an average of 52.5 g CH_4 and 2771 g CO_2 was eructated or respired daily during the grazing period on smooth bromegrass pasture. When measuring ALT cows in gestation in the pen chamber, calves produced, on average, 17 and 37% of cow CH_4 and CO_2, respectively. During the 3 campaigns of brome pasture grazing, calf BW were, on average, 98, 151, and 192 kg, and estimated CH4 were 23, 54, and 84 g animal^{-1} d^{-1}. And CO_2 1,778, 2,844, and 3,790 g animal^{-1} d^{-1}. Relative to the cow contribution during these periods, calves produced 74, 15.3, and 35.3% of the cow CH_4 and 10.8, 17.2, and 22.9% of the cow CO2, respectively. During oat forage grazing calves, on average, contributed 54.6 and 2855 g of CH_4 and CO_2 which was 17 and 18% of cow emissions, respectively. Leão et al. (2018) measured 1089 to 1292 g CO_2 d^{-1} from dairy heifer calves at 45 days of age using snout respirators. Others using EC (Todd et al. 2016 and Dumortier et al. 2021) assumed calves produced 10 to 30% of the total CH_4 of cow production. These, however, were summarized over a short measurement period which spanned the entire period when calves were 30 d to 168 days of age. Assuming calf contribution was constant with time would under or overestimate calf contribution, depending on the size of the calf and production of CO_2 and CH_4 relative to the cow. Some of this overestimation may be due to cow intakes relative to calves in grazed scenarios. Assuming calf contributions are equal to a certain percentage may be adequate in short term-studies. There was a wide array of variability in the proportion of calf CH_4 and CO_2 relative to the total produced by the cow/calf pair. Based on this variability, the calculation used improved the accuracy of the EC method and the assumptions contained in the EC calculation with animal position data. When considering the contribution of the calf over the entire system (preweaning) assigning the calculated value with growth was a more robust estimate than assuming constant contribution relative to the cow over the period.

Carbon Dioxide

Confined Cow

When ALT cows were fed in the pen chamber, cow CO_2 production was 5,945 and 7024 g animal^{-1} for gestation and lactation, respectively. Unlike CH_4, there is no diurnal variation in CO_2 production during the day in any of the diets fed in the pen chamber. Constant respiration to support animal metabolism supports this observation. Production of CO_2 was similar to Chung et al. (2013) 7,383 g animal^{-1} day^{-1}, fed, on average 4.9 kg DM of alfalfa and sainfoin to dry and lactating cows. When cows were grazing corn residue, average cow respiration produced 7400 g CO_2 animal^{-1} d^{-1}. Production when consuming corn residue was less than cows in the CONV system produced CO_2 over all 3 periods of the summer was calculated as 16,500 g CO_2 animal^{-1} day^{-1}. The large increase in CO_2 production in the grazing scenario could be due to both diet digestibility and intake. High values for CO_2 have been measured by others. McGinn et al. (2015) measured CH_4 and CO_2 exchange on grazed pastures at different stocking rates. Cattle respiration CO_2 was assumed to be 4,200 g C (15.4 kg CO_2) animal^{-1}d^{-1}, taken from Boadi et al. (2002) since animals were of similar size.

Less emphasis has been put on measuring CO_2 from animal respiration because it is assumed to be in equilibrium with CO_2 taken in by photosynthesis. This is referred to as biogenic CO_2 which is recycled back into the ecosystem. Research has not focused on CO_2 from animal respiration as a GHG contributing to GWP. Ample CO_2 data has been collected with growing and finishing cattle using indirect calorimeters for the purpose of calculating energy values of feeds (Hales et al., 2012, 2013, 2014, 2017). Production of CO_2 from grazing heifers was measured with the SF_6 tracer method or an open-hood circuit calorimeter. While CH_4 was measured with certainty in both methods, increases in CO_2 variability within and between methods made values suspect. Other methods, such as Greenfeed (C Lock, Rapid City, SD) have measured 6,408 g animal^{-1} day^{-1} from heifers consuming a mixed ration (Manafiazar et al. 2015) and 16,819 g CO_2 animal^{-1} day^{-1} from grazing dairy cows (Hristov et al. 2015). Using similar cattle over different years as Dumortier et al. (2021), Gourlez de la Motte et al. (2018) measured the production of respiration CO_2 from EC and biomass disappearance as 11,001 ± 2933 and 9,167 g CO2 animal^{-1} d^{-1}, respectively. Pinares-Patino et al. (2006) measured CO_2 by grazing Holstein-Friesen heifers (BW = 455 ± 29 and 451 ± 28 kg for years 1 and 2) Authors believed the SF_6 tracer method overestimated CO_2 production, but mean values during early season grazing were 8,744 g animal^{-1} day^{-1} while late-season averaged 10,372.5 g animal^{-1} day^{-1}. Variation in CO_2, similar to CH4, is due to variations in diet, intake, and digestibility. Because of the various physiological states and environments in which CO_2 was measured from the CONV and ALT herds, these data will be valuable additions to the literature summarizing beef cattle CO_2 production due to respiration.

Carbon Balance

Corn Residue

When cattle were grazing the corn residue, background CO_2 flux was determined as the fluxes measured when no cattle were in the footprint. This averaged -282 ± 41 g C m^{-2} or -2.5 g C m^{-2} d^{-1}. When averaged over the grazing period (177 days) this was 30.25 kg C $animal^{-1}$ day^{-1} Animal flux of CH_4 and CO_2 and N_2O were 192.8 and 7400 and 17.5 g $animal^{-1}$ d^{-1} respectively. The residue leftover after corn harvest, when not grazed, will degrade over time. Verma et al. (2005) measured CO_2 exchange over the nongrowing season from 3 nearby Ameriflux EC sites (164 aramet. October 15 to May 10) of 170 to 255 g C m^{-2}. This C release from the ecosystem was from the natural degradation of residue. Historical data from the same experiment stations in Verma et al. (2005) from 2001 to 2013 were summarized. Fluxes during the non-growing season for CO_2 in cornfields were used to calculate average flux during CONV (Oct 26 to March 15) cow grazing. Fluxes in 2008 and 2012 were not included because of a major hailstorm and drought which dramatically affected NEE. For CONV cows grazing corn residue, the comparable C flux of a non-grazed cornfield in the nongrowing season was 406.8 g CO_2 m^{-2} total and 2.91 g CO_2 m^{-2} d^{-1} from October 27th to March 15th in data from 2001 to 2013. The same data were summarized from January 15th to March 15th during the ALT grazing period. Cumulative C loss was 146.5 g m^{-2} and 2.4 g m^{-2} d^{-1} during this late winter/early spring grazing.

Accounting only for C, flux per m^2 was -76.9, -26.9, -7.7, and -44.9 for background C, animal respiration, and CH_4 (4x CO_2e) and N_2O (234x CO_2e). In total this accounts for -156.4 g C m^{-2}. Without the consideration of N_2O flux, C flux is -110.9 and -111.5 g C m^{-2} for non-grazed and grazed fields, respectively. Without loss of N_2O from manure, the rate of natural decomposition of C during the nongrazing season is not different from C degradation due to grazing when stocked at 1 ha cow^{-1}. The flux of N_2O from non-grazed and grazed fields of corn residue is 11.2 and 19.6 mg N ha^{-1} d^{-1}, respectively. After calculating GWP of N_2O and equivalent C from N_2O (GWP 234) in grazed and nongrazed fields the C flux is -144.8 and -121.1 g C m^{-2}, respectively. Degradation of C from grazing does not appear to be different than C loss from the microbial breakdown of residue after harvest. The N_2O from manure provides additional warming potential greater than a non-grazed field.

Carbon dioxide is a measure of heat production (Johnson 2000 and Reynolds 2000). In cattle, ME intake for maintenance is burned as heat production for metabolism. After maintenance requirements are met, 50% of the remaining ME intake is used for heat and the other 50% for growth (Johnson 2000). The maintenance requirement in grazing animals is greater because of the energy expenditure required to walk and graze (Lachica et al. 1999; Agnew and Yan, 2000). In the present study, both bromegrass and oat forage grazing scenarios likely have greater CO_2 production and maintenance requirements than ALT cows measured in the pen chamber. In a similar experiment Gourlez de la Motte et al. (2018) estimated C contribution from respired CO_2 using EC. Measured nighttime fluxes with and without cattle in the footprint were used to calculate total ecosystem respiration and ecosystem respiration. The difference between these two values was the calculated CO_2 from cows. This calculation showed 3.0 +- 0.8 kg C livestock unit^{-1} (LU^{-1}) d^{-1} (11,001 +- 2934 g CO_2 animal^{-1}d^{-1}). For the total grazing period, C from respiration was 208 and 230 g C m^{-2} yr^{-1}. Based on ingested biomass this was 2.5 kg C per LU d^{-1} (6.60 kg DMI assuming grazed forage content 41.6% C and 91.15% OM) (Gourlez de la Motte et al. 2018). Using a similar method, Felber et al. (2016) estimated dairy cow CO_2 emissions to be 4.6 +- 1.6 kg C animal^{-1}d^{-1} (16,868 g +-5,867 CO_2). Assuming average CO_2 production per pair of 11,427 and 20,286 g for grazing bromegrass and oat forage, respectively, brings CO_2 balance to 0%. Both of these values are within the 95% confidence interval measured by Gourlez de la Motte et al. (2018).

Estimate of CONV cow CH_4 and CO_2

For CONV cows, from post-residue grazing (March 16th) until grass turnout (May 1st), cows were fed 11.3 kg DM ground hay d^{-1}. This was the only period in the study for either system when CH_4 or CO_2 was not directly measured. To estimate CO_2 and CH_4 production during this period, individual C balance was calculated. This calculation was done for cows in all environments within these systems. For a detailed description and results from these calculations and carbon balance of cows in each grazing and feeding scenario in this study, refer to the Appendix. Methane was predicted based on NASEM (2016) 237.6 ± 55.3 g CH_4 daily. Carbon balance was used to calculate estimated CO_2 production during this phase. Assuming a TDN of 48.28% results in OM intake of 10,301 g. Assuming OM is 42% C, C intake is 4,285 g daily. Carbon loss due to feces is 2,216 g and conceptus retention is 12 g daily. To have a net-zero C balance, C from CO_2 must be 2057 g animal^{-1} day^{-1}. Assuming CO_2 is 27.27% carbon, CO_2 production is predicted to be 7,543 g animal^{-1} day^{-1}. These values were used to compute GHG production estimates for the CONV system during this period.

System GHG emissions

Overall CH_4 emissions in each system are calculated as CO_2e (Figures 10, 11, and 12). Measurements of CH_4 and CO_2 could not be completed on every cow replication group in each treatment, especially in the grazed scenarios. Therefore, traditional statistical analysis of the 2 systems could not be completed, but an estimate of lower and upper limits for each estimate was calculated. The 95% confidence limits are presented for all DMI, CO_2, and CH_4. These are presented in Tables 9a, b, and c. While the numerical difference in the mean value for CH_4 production is discussed below, the multiple sources of variation and lack of replicated data in these 2 systems make it impossible to draw conclusions about one system compared to the other.

In all discussion below, unless otherwise noted, CH_4 is considered to have 4 x GWP of CO_2 (Balcombe et al., 2018). During gestation, cows in the CONV system produced a total of 153.1 kg (± 25) CO_2e from CH_4 while ALT cows produced only 113.2 (±13.3) pair^{-1} total. This was due to less CH_4 by cows fed in drylot (137 g animal^{-1} day^{-1}) compared to CONV cows grazing corn residue (192 g animal^{-1} day^{-1}). During lactation, CONV cows produced more CO_2e from CH_4 over the entire period (3653 ± 815 and vs 2431 ± 308 kg CO_2e) than ALT cows. The chart of relative contribution of CH_4 for each system is shown in Figure 10. For the CONV system, the proportion of CO_2e kg^{-1} HCW from gestation, lactation, growing, and finishing were 28.3, 45.7, 12.3, and 13.6% for respectively. In the ALT system, these percentages were 23.8, 40.1, 13.4, and 22.7, respectively. The greater proportion of GHG during the finishing phase in the ALT system was due to greater DOF (148 vs 183 for CONV and ALT, respectively). And therefore, more total CH_4 (73.7 vs 108.0 CO_2e from CH_4 for CONV and ALT, respectively) was observed. Beauchemin et al. (2010) calculated a similar life-cycle assessment on the Canada beef production system based on an 8-year cycle to account for cow longevity and culling. Cow/calf, breeding stock, backgrounding, and finishing periods produced 61, 19, 8, and 12% of all CO_2e. This did include emissions from manure, energy, and soil contributions from the entire system. Enteric methane emissions were 79, 3, 2, 7, and 9% from cows and developing heifers, bulls, calves, backgrounders, and finishers respectively. Basarab et al. (2012) modeled GHG emissions from a calf-fed and yearling-fed production systems. Calf-fed production systems that used growth-promoting technologies averaged 70% from cow, 15% for feeding of the calf, and 15% for heifer development, cull cow feeding, and bull development. Yearling fed systems required 52%, 35, and 13% for cow, feeder, and other herds since yearlings were backgrounded 252 days before the feedlot phase. However, enteric emissions were not measured but rather were based on IPCC 2006 guidelines and nitrogen excretion from the NRC 2000. Basarab et al. (2012) reported total GHG production from enteric methane to be 10.7 and 11.2 kg CO_2e kg^{-1} CW. Total CO_2e production was greater (19.87 and 21.2, calf and yearling fed, respectively) after accounting for additional CH_4, CO_2, and N_2O from manure. Total production was reduced by 10 and 15% after accounting for on-farm crop soil C sequestration. Total CO_2e production, including energy inputs, accounted for 54%, 26, 9, 11 from enteric methane, manure, energy use, and cropping, respectively.

Across all 4 production phases, the CONV system produced 540 (±90) kg CO_2e from CH_4 $animal^{-1}$ d^{-1} and 1.68 (±0.28) CO_2e kg^{-1} HCW from CH_4. The ALT system produced 476 (±78) kg CO_2e from CH_4 and with lower HCW produced per cow exposed (303.2 vs 321.0 for ALT and CONV, respectively) the ALT system produced 1.57 (±0.25) kg CO_2e kg^{-1} HCW. Emissions of CH_4 from Rotz et al. (2019) were equal to 1.9 kg CO_2e after converting to CH_4 using a GWP of 4 which is slightly greater than CONV and ALT systems. The lower production of HCW per cow exposed in the ALT system is a combination of lower weaning rate (82.3 vs 87.2% $P = 0.27$) and calving rate (90.0 vs 91.2% $P = 0.71$). Indications of this result were shown in differences in weaning BW (229 vs 184 kg) and kg weaned per cow exposed (199 vs 150 kg) for CONV and ALT, respectively. Few calves entered the post-weaning feeding period, and, had similar HCW (381 vs 388 $P = 0.14$), this resulted in overall less CW per cow exposed. Essentially, most of the reduction in CH_4 production during gestation in the ALT system (264 kg $animal^{-1}$ CO_2e difference) was lost during the finishing phase (201 kg CO_2e $animal^{-1}$ difference). The lack of performance pre-weaning had a large impact on the overall production of beef from the ALT system, therefore increasing the amount of CH_4 produced kg^{-1} CW. In an assessment of the Canada beef production system, enteric emissions from the entire herd accounted for 13.7 kg CO_2e kg^{-1} CW (Beauchemin et al. 2010) when using 23 as GWP for CH_4 (2.38 kg for GWP of 4 for CH_4). Some differences were due to emissions from replacement females (19% of all emissions in Beauchemin et al., 2010) which were not measured in this study. In the current study, without including CO_2 from respiration but adding modeled N_2O emissions from Beauchemin et al. (2010) (described below), total emissions are 7.5 ± 0.3 and 7.4 ± 0.3 CO_2e kg^{-1} HCW for CONV and ALT, respectively. The ALT and CONV production systems produced similar emissions per kg HCW and are similar to other life cycle assessments. Rotz et a. (2019)

estimated total GHG emissions across U.S. beef production, and, after converting those values using GWP of 4 and 234 for CH_4 and N_2O, was 6.5 kg CO_2e kg^{-1} CW.

System carbon balance

The GHG not adequately measured was N_2O. Emissions from N_2O were measured in grazed scenarios, however, in the pen chamber, N_2O could not be measured. According to Beauchemin et al. (2010), N_2O emissions from pasture and feedlot manure are responsible for 23% of all beef production system emissions. Feedlot and pasture soil N_2O fluxes are responsible for 4% of all emissions. Modeled values from Beauchemin et al. (2010) were used to complete the estimate of all emissions from these beef production systems. Additional emissions from manure and N_2O according to Beauchemin et al. (2010) would result in an additional 37% more CO_2e (5% manure CH_4, 23% manure N_2O, 4% soil N_2O, and 5% energy CO_2) and a 35% increase based on Rotz et al. (2019). Rotz et al. (2019) estimated total emissions of CH_4, and N_2O as 0.482 kg and 19.9 g per kg CW, respectively. These multiply to 11.1 and 5.9 kg CO_2e per kg CW resulting in 17.0 kg CO_2e per kg CW. Beauchemin et al. (2010) did not account for CO_2 from respiration which is considered biogenic CO_2. Expressing emissions on kg CO_2e basis, emissions from manure CH_4, manure N_2O, soil N_2O, and energy CO_2 were 1.1, 5.0, 0.82, and 1.2 kg (8.0 kg total) CO_2 per kg CW using GWP of 23 and 298 for CH_4 and N_2O, respectively. When applying the 4x and 235 x CO_2 for CH_4 and N_2O, respectively, the emissions reduced to 0.19, 3.9, 0.65, and 1.1 kg CO_2e per kg CW or a total of 5.8 kg CO_2e. Totals of 8.0 (using 23x CO_2e and 298 for CH_4 and N_2O, respectively) and 5.8 kg (using 4x CO_2e and 234 for CH_4 and N_2O, respectively) CO_2e kg^{-1} HCW were applied both CONV and ALT systems as estimates of GHG not associated with enteric fermentation or animal respiration (Table 9a). These non-animal associated GHG emissions were divided equally over gestation, lactation, growing, and finishing phases. After the addition of Beauchemin et al. (2010) non-animal emissions, the needed amount of sequestered C for each system for beef production to be C neutral was calculated (Table 9b). For all sequestration values described below, positive values are associated with carbon uptake, and negative values are associated with a release of carbon from the ecosystem. In confined scenarios for cows and calves, as well as grazing corn residue, no growing biomass was available to sequester C from the cattle ecosystem. For CONV cows, grazing brome pasture occurred over 177 days and the stocking rate on the measured group was 12,100 m^2 per pair. In the present study CO_2e from all enteric CH_4, respiration CO_2, and modeled manure emissions resulted in 24.3 (±2.3) kg CO_2e per kg CW per cow exposed or 7,784 kg CO_2e per cow-calf pair when using 4x CO_2e and 234 for CH_4 and N_2O, respectively. To offset these emissions, the pasture would need to sequester 175 (± 12) g C m^{-2} yr^{-1} or 0.99 (± 0.10) g C m^{-2} d^{-1} of the grazing period. For the ALT system, cows graze oat forage for only 84 d yr^{-1} and stocking density is 10,700 g m^2 cow^{-1} on the tested group. Emissions average 24.9 (±2.9) kg CO_2e per kg CW or 7,558 kg CO_2e per pair. Needed C sequestration is 193 (± 23) g C m^{-2} yr^{-1} or -2.30 (± 0.27) g m^{-2} d^{-1}.

Measured sequestration of C in the bromegrass pasture was 282 ± 41g C m^{-2} yr^{-1} (0.77 g C m^{-2} d^{-1} over the year or 1.59 g C m^{-2} d^{-1} over the grazing period) (Table 9c). This was enough C to sequester all CH_4, N_2O, and CO_2 from the entire production system (gestation, lactation, growing, and finishing) with 78.6 g C m^{-2} yr^{-1} surplus C or 10.9 kg CO_2e per kg CW per cow exposed and 3487 kg CO_2e $pair^{-1}$. Expressing CH_4 and N_2O

emissions using 23 and 298 GWP, respectively, also resulted in a surplus of C (5.1 g C m^{-2} yr^{-1} surplus C or 0.70 kg CO_2e per kg CW per cow exposed and 224.1 kg CO_2e $animal^{-1}$). For the ALT cows grazing cover crops, C sequestration was 138 ± 43 g C m^{-2} yr^{-1} or (-0.38 g C m^{-2} d^{-1} over the year or 1.64 g C m^{-2} over the grazing period) which was less than the C sequestration needed (250 or 193 g C $m\text{-}^{2}$ yr^{-1} for 4x CO_2 or 23x CO_2, respectively, for CH_4). This resulted in the ALT system being a net generator of CO_2e (7.1 kg CO_2e per kg CW, 54.6 g C m^{-2} yr^{-1}, or 2143 kg CO_2e per cow exposed). Expressing CH_4 and N_2O emissions using 23 and 298 GWP, results in the ALT system as a greater net generator of C CO_2e (16.7 kg CO_2e per kg CW, 112.2 g C m^{-2} yr^{-1}). When computing C balance of a pasture overtime at 2 stocking densities, McGinn et al. (2015) considered C to be 25x GWP, and therefore, C balance of the pasture was calculated based on CO_2e, not solely g of C from CO_2 or CH_4. No distinction was made between CO_2 sourced from animal or ecosystem respiration. When stocking at 0.1 or 0.2 animals ha^{-1} the pasture was a sink of -40 kg C ha^{-1} yr^{-1} (4 g C m^{-2} yr^{-1}) when stocking at 0.1 animals ha^{-1} or a source of 7 kg ha^{-1} yr^{-1} (0.7 g m^{-2} yr^{-1}) when stocking at 0.2 animals ha^{-1}. Felber et al. (2016) calculated net carbon flux with and without grazing dairy cattle influence. On an annual basis, sequestration was comparable between including (2042 g C $m\text{-}^{2}$ yr^{-1}) and excluding cows (2061 g C $m\text{-}^{2}$ yr^{-1}) which resulted in the calculation of C from respiration (4.6 kg C $animal^{-1}$ d^{-1}). Grazing lands, after accounting for animal respiration, took up 68 g C m^{-2} annually. Gourlez de la Motte et al. (2018) monitored Belgian Blue cows and calves grazing in continuous (CONT) or rotationally (RG) paddocks with greater stocking density. Carbon intake was estimated from biomass samples before and after grazing, with the accounting for grass growth from non-grazed enclosures. Net carbon sequestration for CONT ranged from -49 in May/June to 123 g C m^{-2} while RG ranged from -57 to 153 g C m^{-2} in the same period. The weighted average over the grazing season after accounting for animal respiration was 74 and 88 g C m^{-2} uptake by the pasture for continuous and rotational grazing, respectively. S

Net sequestration after removal of only cow and calf respiration in CONV cows was 233 g C m^{-2} yr^{-1} in the present trial greater than others (Felber et al. 2016, Gourlez de la Motte et al. 2018 and McGinn et al. 2015), but periods within those trials were sequestered more than 153 g C m^{-2}. Summary of CO_2e from CH_4, CO_2, and N_2O relative to C sequestration in gestation, lactation, growing and finishing phases is presented in Table 10.

Application and limitations of C sequestration

The results from the present trial show promise that perennial grasslands in the existing U.S. beef system can sequester most or all emissions from the cattle in their respective system. Grazing annual forages similar to oat forage in the ALT system results in less C sequestration than perennial grasses. Others have theorized ways of optimizing that sequestration. Teague et al. (2016) theorized that adopting 25, 50, or 100% regenerative adaptive multipaddock (AMP) conservation grazing across the entire industry could change the C status of current livestock and crop production from an emitter of 0.27 Gt C $yr^{-1}$to a sink of 0.7 Gt C yr^{-1}. The AMP method is designed to mimic ancient grazing patterns by the large herd of ruminants across the plains. More recent evidence suggests that using AMP can retain 13% more soil C and 9% more soil N than continuous grazing (Mosier, et al. 2021).

Stanley et al., (2018) estimated that grain-finished systems produce 6.09 kg CO_2e kg^{-1} CW. Grass-finished systems can produce 9.62 kg CO_2e kg^{-1} CW, mostly due to enteric methane production and reduced CW (280.2 vs 405.8 kg). However, utilizing AMP, soil C flux can decrease CO_2e by increasing C soil flux by 3.59 Mg ha^{-1} yr^{-1}. In the current study, brome pasture can sequester 2.8 Mg C ha^{-1} yr^{-1} and cover crops sequestered 1.4 Mg C ha- yr^{-1}. Utilizing AMP results in beef production becoming a C sink by decreasing grass finishing from 9.62 kg CO_2e to -6.65 CO_2e kg CW (Stanley et al., 2018). However, Stanley et al. (2018) made no adjustments for CO_2 from animal respiration which accounts for 69% and 70% CO_2e from the CONV and ALT system, respectively. Emissions of CO_2 from respiration must be considered when discussing C sequestration since all respired C is part of the balance between carbon loss and gain in these environments. In addition, Stanley et al. (2018) only considered the finishing phase of production without any consideration for existing C sequestration in the pre-feedlot stage. Lastly, Stanley et al. (2018) based sequestration and grass-finished performance data on calves grazing predominantly alfalfa which is higher quality than many grasslands across the U.S. While utilizing AMP may be a carbon-neutral or sink relative to conventional production, practical application of AMP utilization across all regions and seasons is limited. Minasny et al. (2017) theorized the practical implications of increasing soil C worldwide. Only managed agricultural soils would be able to achieve the increase in C in the top 1 m of soil which would be enough to offset 20 – 35% of all anthropogenic GHG emissions. A major limitation is soil C saturation. Soil C sequestration rates range from 0.22 to 8.0 Mg C ha^{-1} yr^{-1} (Minasny et al., 2017).

An important consideration is the sustainability of C sequestration in soils and the saturation percentage of C in soils. Chen et al. (2019) showed soil C sequestration potential is greatest, in order, for grasslands, forests, and cropland, respectively, and soil C saturation has been modeled, but has not been well measured. McNally et al. (2017) modeled soil C in New Zealand soils. An estimated 124 Mt C ha^{-1} were needed to offset all anthropogenic emissions. It was estimated that 10 to 42 t C ha^{-1} could be sequestered before, depending on soil type, saturation point would occur. Additional years of data within the production systems described in this study must be completed to measure the repeatability of C sequestration. In addition, differing environments, soil, and forage types must be tested to quantify the dynamics of C sequestration across grazing ecosystems.

IMPLICATIONS

The data contained in this work may be the most extensive measurement of cattle in various productions systems to date. Multiple models in the literature estimate emissions from the different segments of beef production. This research, using new eddy covariance techniques, measures the uptake of C from grazed ecosystems and measures emissions from all cattle in two systems from the time of conception of the calf to the time of slaughter. Depending on the greenhouse gas metrics used, the conventional beef production system is a C sink or C neutral when utilizing cool-season grasses during the gestation and lactation phases of beef production. Limit feeding harvested feeds to cows in confinement to meet nutrient needs resulted in less CO_2 and CH_4 emissions per animal per day. Sequestration from grazing annual cover crops removed 42 to 72% of emissions from the entire system, depending on the greenhouse gas metrics used. The carbon balance data in combination with animal performance data generated can be used to adopt practices that minimize production of greenhouse gases and maximize animal performance. However, more research is needed studying systems across multiple years and in varying grazing scenarios. Management practices cannot be adopted given the lack of information across diverse ecosystems of beef production. When these knowledge gaps are filled management practices can be adopted that maximize animal performance and minimize emissions.

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TABLES

Table 3.1. Ingredient composition of confinement diet fed to alternative (ALT) cow-calf system by year during pen-scale GHG measurement[1]

	Gestation			Lactation		
Ingredient, %	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
MDGS	55.00	55.00	35.00	55.00	55.00	35.00
Corn silage			40.00			
Forage Silage						21.43
Wheat straw	40.00	40.00	20.00	41.33		40.00
Oat straw					41.92	
Supplement	5.00	5.00	5.00	3.67	3.08	3.57
Fine ground corn	2.47	2.49	2.49	1.79	1.80	1.83
Beef trace mineral and salt premix	--	1.79	1.79	--	1.31	1.31
Limestone	1.98	0.57	0.57	1.45	0.42	0.42
Salt	0.30	--		0.22	--	
Tallow	0.13	0.13	0.13	0.09	0.09	0.09
Beef trace minerals premix	0.10	--		0.07	--	
Insect growth regulator	--	--		0.02	0.02	0.02
Vitamin A-D-E premix	0.02	0.02	0.02	0.01	0.01	0.01
Monensin	0.01	0.02	0.02	0.01	0.01	0.01

[1] Treatment = alternative cow-calf system (ALT) calving in July/August and utilizing drylot, fall forage oat grazing, and corn residue grazing

[2] All values represent on a DM basis

Table 3.2. Nutrient profile and estimated methane production from grazed forages in both CONV and ALT systems.

	Bromegrass	Oat Forage	Corn residue
IVOMD[1]			
Early	52.8	62.7	59.1
Mid	49.9	62.7	57.1
Late	52.7	47.4	52.1
TDN[2]	61.7	63.0	49.8
Fat, % of OM[3]	1.64	3.66	1.44
Protein % of OM[2,3]	10.39	7.78	6.07
Carbohydrate, % of OM[3]	81.18	70.15	81.39

[1] In vitro organic matter digestibility was measured during bromegrass pasture grazing and oat forage grazing early, mid, and late during subsequent grazing. Corn residue values were adapted from Burken (2014), Gutierrez-Ornelas and Klopfenstein (1991), and Lamm and Ward (1981)

[2] Measured crude protein analysis from diet sample from obtained from cannulated steers for bromegrass and oat forage. Cornstalk values from NASEM (2016)

[3] Using standard book values from NASEM (2016)

Table 3.3. Parameters from GPS and eddy covariance flux at different grazing intervals within ALT and CONV systems[1]

	Corn Residue	Smooth Bromegrass			Oat Forage
Stocking rate, m^2 per animal	10500		12100		10700
Start	12/6/2019	6/3/2020	7/17/2020	9/2/2020	10/28/2020
End	3/15/2020	7/7/2020	8/21/2020	10/2/2020	12/28/2020
GPS					
Before Gap filling	18.18	23.09	18.02	0.00	14.20
After-gap filling	16.05	11.12	10.68	0.00	8.15
Methane					
No calf adjustment[3]					
Coefficient		332.16	417.06	321.87	364.50
Intercept		0.18	0.24	0.10	0.00
R^2		0.83	0.62	0.85	0.87
Calf Adjustment					
Coefficient Mean	191.9	300.5	353.6	237.9	309.2
Coefficient lower 95 CI[5]	166.0	249.8	245.9	181.0	266.1
Coefficient upper 95 CI[5]	217.7	351.1	461.3	294.8	352.3
SE	13	24.9	53	27.8	21.50
P-Value[4]	<0.01	<0.01	<0.01	<0.01	<0.01
Intercept Mean	0.05	0.17	0.24	0.10	0.01
Intercept lower 95 CI[5]	0.01	0.08	0.02	-0.02	-0.08
Intercept upper 95 CI[5]	0.10	0.26	0.46	0.37	0.10
SE	0.02	0.04	0.11	0.13	0.04
P-Value[4]	0.01	<0.01	0.03	0.43	0.77
R^2	0.70	0.82	0.57	0.72	0.80
Carbon Dioxide					
Coefficient Mean	7400		17955		15625
Intercept Mean	1		-4.14		2.11
Coefficient lower 95 CI[5]	5784		12179		13425
Coefficient upper 95 CI[5]	9015		23730		17826
SE	812		2823		1098
P-Value[4]	<0.01		< 0.01		<0.001
R^2	0.50		0.58		0.78
C Flux					
Background, g C m^{-2} d^{-1}	76.90				
With cattle, g C m^{-2}	111.50				
Sequestration, g C m^{-2}			282.00		138.00

[1] At the end of each campaign cattle GPS units were removed. Data were downloaded and batteries were charged before being put back on.

[2] The mean location of each animal over each 30-minute flux period was calculated. Animals with no GPS location in a given 30-minute flux period were a result of GPS malfunction. Gap-filling analysis was done to calculate animal locations based on previous and next GPS location. This decreased percentage of animals without GPS location.

[3] Coefficient determined from the regression of animals in the tower footprint with flux (g CH_4) after adjusting for estimated flux from calves based on estimated calf size.

[4] Values of coefficient and intercept are different from zero if $P < 0.05$

[5] Range of 95% confidence interval

Table 3.4. Methane and carbon dioxide production of calves pre and post weaning

Source	Body wt, kg	CH_4, g	CO_2, g	Method
ALT calves pre-weaning	84.1	15.4	1522.6	Whole body chamber
ALT calves pre-weaning	85.0	8.8	1536.1	Whole body chamber
ALT calves pre-weaning	91.8	24.1	2054.0	Whole body chamber
ALT calves pre-weaning	83.4	18.6	1944.3	Whole body chamber
ALT calves pre-weaning	98.6	20.1	259.6	Whole body chamber
ALT calves pre-weaning	90.3	9.8	1519.4	Whole body chamber
ALT calves pre-weaning	104.7	19.1	1315.4	Whole body chamber
ALT calves pre-weaning	96.3	16.1	1589.2	Whole body chamber
ALT calves post-weaning	266.1	129.0	5851.9	Whole body chamber
ALT calves post-weaning	254.1	143.7	5436.5	Whole body chamber
ALT calves post-weaning	238.5	138.6	5094.6	Whole body chamber
ALT calves post-weaning	252.7	145.2	5813.0	Whole body chamber
ALT calves post-weaning	213.6	94.2	3391.1	Whole body chamber
ALT calves post-weaning	236.1	114.4	4571.3	Whole body chamber
ALT calves post-weaning	211.4	112.1	3901.3	Whole body chamber
ALT calves post-weaning	200.5	105.6	3644.6	Whole body chamber
Stackhouse et al. (2011)	159.0	47.8	5411.0	Whole body chamber
Stackhouse et al. (2011)	54.0	0.0	1391.8	Whole body chamber
Ramirez-Restrepo et al. (2016)	92.0	39.3		SF_6 tracer
Ramirez-Restrepo et al. (2016)	148.0	61.3		SF_6 tracer
Ramirez-Restrepo et al. (2016)	159.0	55.4		SF_6 tracer
Ramirez-Restrepo et al. (2016)	183.0	78.5		SF_6 tracer
Ramirez-Restrepo et al. (2016)	151.0	48.0		Indirect Calorimeter
Ramirez-Restrepo et al. (2016)	172.0	76.2		Indirect Calorimeter
Ramirez-Restrepo et al. (2016)	196.0	69.2		Indirect Calorimeter
Ramirez-Restrepo et al. (2016)	216.0	87.3		Indirect Calorimeter

Table 3.5. Production of CH_4 and CO_2 from cows and calves in grazing and confinement from conventional (CONV) cow-calf system[1]

Gestation	CONV				
Corn Residue Grazing[2]	Per Pair	Lower 95	Upper 95	Cow only	Calf Only
CH_4, g		166.0	217.7	191.9	
CO_2, g		7000.0	7800.0	7400.0	
DMI, kg		4.7	13.7	8.9	
GE loss, Mcal		2.2	2.9	2.5	
TDN, % of DMI[3]	51.14				
IVOMD, %[4]	65.6				
Grass hay[5]					
CH_4, g		182.3	356.5	237.6	
CO_2, g		7135.642	7928.524	7543	
DMI, kg				11.3	
GE loss, Mcal	3.1				
TDN, % of DMI	48.3				
Lactation					
Grass Pasture – Early season[6]					
CH_4, g	322.76	272.1	373.44	300.46	22.3
CO_2, g	18278.4	13957.4	25508.4	16500	1778.4
DMI, kg	14.2	7.9	21.6		
GE loss, Mcal	4.0	3.3	4.6		
TDN, % of DMI	51.66				
IVOMD, %	51.67				
Grass Pasture – Mid season[7]					
CH_4, g	407.91	300.2	515.6	353.61	54.3
CO_2, g	19344	15023	26574	16500	2844
DMI, kg	16.7	7.7	28.4		
GE loss, Mcal	4.7	3.2	6.1		
TDN, % of DMI	51.66				
IVOMD, %	50.51				
Grass Pasture – Late season[8]					

CH_4, g	322.0	265.1	378.9	237.9	84.1
CO_2, g	20290.4	15969.4	27520.4	16500	3790.4
DMI, kg	11.2	5.7	18.1		
GE loss, Mcal	3.1	2.4	3.9		
TDN, % of DMI	51.7				
IVOMD, %	48.6				

	Per Pair	Lower 95	Upper 95
CO_2e, CO_2 only, kg	2302.7	1870.7	2805.0
CO_2e, CH_4 only, kg	4803.6	3963.3	6157.9
CO_2e total, kg	7106.4	5834.0	8962.9

[1] Treatment = conventional cow-calf system (CONV) utilizing summer pasture, corn residue, and calving in April/May

[2] Grazing period October 27 to March 15 for CONV and January 16 to March 15 for ALT. Values from eddy covariance measures

[3] Determined from NASEM (2016) values

[4] Based on measured fermented samples by diet sampling using cannulated steers during grazing period

[5] CONV cows fed bromegrass hay from March 15th to May 1st. Methane values from NASEM 2016 for cows fed 11.3 kg bromegrass hay

[6] Grazing period May 3rd to July 7th, 2020. Values determined using eddy covariance and individual animal locations.

[7] Grazing period July 8th to September 1st, 2020. Values determined using eddy covariance and individual animal locations.

[8] Grazing period September 1st to October 25, 2020. Values determined using eddy and individual animal locations.

Table 3.6. Production of CH_4 and CO_2 from cows and calves in grazing and confinement from an alternate (ALT) cow-calf system[1]

Gestation		ALT			
Corn Residue Grazing[2]	Per Pair	Lower 95	Upper 95	Cow only	Calf Only
CH_4, g		166.0	217.7	191.9	
CO_2, g		7000.0	7800.0	7399.7	
DMI, kg		4.7	13.7	8.9	
GE loss, Mcal		2.2	2.9	2.5	
TDN, % of DMI[3]	51.1				
IVOMD, %[4]	65.6				
Limit feed- confinement[5]					
CH_4, g		122.4	151.1	137.0	
CO_2, g		5100.1	6789.9	5945.0	
DMI, kg				6.9	
GE loss, Mcal	1.8				
TDN, % of DMI	66.0				
Lactation					
Limit feed-confinement[6]					
CH_4, g	175	158.2	192.5	149.4	25.6
CO_2, g	7024	5765	8283	5131.9	1892.2
DMI, kg	9.1				
GE loss, Mcal	2.3				
TDN, % of DMI	65.1				
Grazing secondary annual forage[7]					
CH_4, g	363.8	320.7	407.0	309.2	54.6
CO_2, g	18481.0	16281.0	20682.0	15625.0	2856.0
DMI, kg	23.2				
GE loss, Mcal	4.1				
TDN, % of DMI	58.3				
IVOMD, %	52.5				
	Per Pair	Lower 95	Upper 95		

CO_2e, CO_2 only, kg	1748.46	1550.52	1946.52
CO_2 equiv, CH_4 only, kg	3414.52	2977.99	3851.17
CO_2e total, kg	5162.97	4528.51	5797.69

1Treatment = Alternative cow-calf system (ALT) calving in July/August and utilizing drylot, fall forage oat grazing, and corn residue grazing

2Grazing period October 27 to March 15 for CONV and January 16 to March 15 for ALT. Values from eddy covariance measures

[3] Determined from NASEM (2016) values

[4] Durning corn residue grazing IVOMD values from Burken (2014) values during oat forage grazing were measured using fermented samples by diet sampling using cannulated steers during grazing period

[5] ALT cows fed in confinement from July 18th to October 23rd, 2020. Diet was 55% modified distillers grains plus solubles (MDGS), 41.3% wheat straw, and 3.7% supplement year 1 and 2 and 35 % MDGS, 20% forage silage, 40% wheat straw, and 5% supplement year 3, DM basis. Values determined using pen-scale chamber.

[6] Grazing period October 27, 2020 to January 15, 2021 for ALT cows. Values determined using eddy covariance and individual animal locations.

[7] Dry matter intake (DMI) estimated based on gross energy (GE) loss from CH4. NASEM 2016 median CH_4 loss due to GE used to estimate DMI. This is an estimate for C balance estimation. All comparisons of CH4 production based on per cow per day production and no consideration for DMI

Table 3.7. Overall CH_4 and CO_2 production in pasture-based (CONV) and confinement based (ALT) cow/calf production systems during gestation and lactation phases

	CONV			ALT		
Gestation	Mean	Lower[3]	Upper[3]	Mean	Lower[3]	Upper[3]
DMI, kg	9.54	6.38	13.06	7.57	6.20	9.10
Days	188	188	188	183	183	183
CH_4						
CH_4 per kg DMI, g	21.33	26.66	19.38	20.43	22.00	18.97
CH_4 per animal per day, g	203.53	170.14	253.16	154.68	136.45	172.58
Total CH4, kg	38.26	31.99	47.59	28.31	24.97	31.58
CO_2						
CO_2 per kg DMI, g	779.47	838.19	551.53	847.25	858.14	721.96
CO_2 per animal per day, g	7436.51	5349.23	7204.66	6414.00	5322.90	6566.50
Total CO_2, kg	1398.06	1005.66	1354.48	1173.76	974.09	1201.67
Global warming potential						
CO_2e from CH4, kg 4x CO_2	153.06	127.94	190.38	113.23	99.88	126.33
CO_2e from CH4, kg 23 x CO_2	880.07	735.68	1094.67	651.06	574.31	726.40
CO_2e from CO_2, kg	1398.06	1005.66	1354.48	1173.76	974.09	1201.67
CO_2e per animal	1551.12	1133.60	1544.85	1286.99	1073.97	1328.00
CO_2e per kg HCW	4.83	3.53	4.81	4.24	3.54	4.38
Lactation						
DMI, kg	14.05	7.14	22.66	15.63	10.69	24.61
Days	177	177	177	182	182.00	182.00
CH_4						
CH_4 per kg DMI, g	24.88	39.03	18.54	16.77	21.81	11.85
CH_4 per animal per day, g	349.46	278.81	420.12	262.16	233.21	291.48
Total CH_4, kg	61.86	49.35	74.36	47.71	42.44	53.05
CO_2						
CO_2 per kg DMI, g	773.4	382.2	1427.8	734.2	486.9	1182.3
CO_2 per animal per day, g	19240.7	14919.7	26470.7	12311.8	10618.5	14005.6
Total CO_2, kg	3405.61	2640.79	4685.32	2240.8	1932.6	2549.0
Global warming potential						

CO_2e from CH_4, kg 4x CO_2	247.42	197.39	297.45	190.85	169.78	212.20
CO_2e from CH_4, kg 23 x CO_2	1422.67	1135.02	1710.33	1097.39	976.22	1220.13
CO_2e from CO_2, kg	3405.6	2640.8	4685.3	2240.8	1932.6	2549.0
CO_2e per animal	3653.03	2838.19	4982.77	2431.61	2102.35	2761.22
CO_2e per kg HCW	11.4	8.8	15.5	8.0	6.9	9.1

[1] Treatment = conventional cow-calf system (CONV) utilizing summer pasture, corn residue, and calving in alternative cow-calf system (ALT) calving in July/August and utilizing drylot, fall forage oat grazing, and corn residue grazing

[2] All values are expressed on per animal basis, unless otherwise noted.

[3] Global warming potential for CO_2 =1 and CH_4 = 23. These calculations used to calculate CO_2 equivalents (CO_2e)

[4] Upper and lower values for all parameter calculated from the minimum and maximum values of the 95% confidence interval for DMI, CH_4, and CO_2. The calculations of mean total CH_4 and CO_2 were repeated to determined value ranges for each system.

[5] Production per cow used the metric of kg of HCW per cow exposed to bull. This accounted for differences in conception, weaning, and death loss from conception to slaughter. Calves in the ALT system, on average, were 44 kg lighter at weaning

Table 3.8. Overall CH_4 and CO_2 production in pasture-based (CONV) and confinement based (ALT) cow/calf production systems during growing, and finishing phases

	CONV			ALT		
Growing	Mean	Lower[3]	Upper[3]	Mean	Lower[3]	Upper[3]
DMI, kg	8.9	8.7	9.2	8.7	8.4	8.9
Days	116	116	116	116	116	116
CH_4						
CH_4 per kg DMI, g	16.1	14.6	17.7	15.7	14.9	15.5
CH_4 per animal per day, g	121.8	109.7	134.1	122.9	107.0	138.7
Total CH4, kg	16.7	15.1	18.3	15.9	14.7	17.1
CO_2						
CO_2 per kg DMI, g	656.5	578.9	729.7	599.4	543.7	655.2
CO_2 per animal per day, g	4948.0	4430.0	5466.0	4713.0	3893.0	5534.0
Total CO_2, kg	679.5	602.6	756.6	603.3	550.6	627.1
Global warming potential						
CO_2e from CH4, kg 4x CO_2	66.75	60.52	73.00	63.50	58.73	68.29
CO_2e from CH4, kg 23 x CO_2	383.82	347.99	419.75	365.14	337.71	392.68
CO_2e from CO_2, kg	679.5	602.6	756.6	603.3	550.6	627.1
CO_2e per animal per d	746.23	663.12	829.60	666.78	609.33	695.39
CO_2e per kg HCW	2.3	2.1	2.6	2.2	2.0	2.3
Finishing						
DMI, kg	10.6	10.1	11.0	10.8	10.5	11.1
Days	148.0	148.0	148.0	183.0	183.0	183.0
CH_4						
CH_4 per kg DMI, g	125.0	105.0	145.0	145.2	104.7	185.7
CH_4 per animal per day, g	11.8	10.2	13.3	13.4	9.9	16.9
Total CH_4, kg	18.4	16.2	20.6	27.0	17.9	36.1
CO_2						
CO_2 per kg DMI, g	716.9	655.0	778.7	661.9	533.7	790.1
CO_2 per animal per day, g	7551.0	7151.0	7953.0	7111.0	5892.0	8330.0
Total CO_2, kg	1127.2	1004.0	1243.0	1293.6	1078.0	1513.3

Global warming potential						
CO_2e from CH_4, kg 4x CO_2	73.7	64.7	82.3	108.0	71.6	144.4
CO_2e from CH_4, kg 23 x CO_2	423.6	372.1	473.0	620.7	411.7	830.3
CO_2e from CO_2, kg	1127.2	1004.0	1243.0	1293.6	1078.0	1513.3
CO_2e per animal per d	1200.8	1068.7	1325.3	1401.6	1149.6	1657.7
CO_2e per kg HCW	3.7	3.3	4.1	4.6	3.8	5.5
HCW per cow exposed[5]	321.0	321.0	321.0	303.2	303.2	303.2

[1] Treatment = conventional cow-calf system (CONV) utilizing summer pasture, corn residue, and calving in an alternative cow-calf system (ALT) calving in July/August and utilizing drylot, fall forage oat grazing, and corn residue grazing

[2] All values are expressed on per animal basis, unless otherwise noted.

[3] Global warming potential for CO_2 =1 and CH_4 = 23. These calculations used to calculate CO_2 equivalents (CO_2e)

[4] Upper and lower values for all parameter calculated from the minimum and maximum values of the 95% confidence interval for DMI, CH_4, and CO_2. The calculations of mean total CH_4 and CO_2 were repeated to determined value ranges for each system.

[5] Production per cow used the metric of kg of HCW per cow exposed to bull. This accounted for differences in conception, weaning, and death loss from conception to slaughter. Calves in the ALT system, on average, were 44 kg lighter at weaning

Table 3.9a. Overall production of enteric methane (CH_4) and carbon dioxide (CO_2) from respiration in gestation, lactation, growing and finishing phases. Required C sequestration per unit of pasture or cover crop area is calculated to make beef production carbon neutral based on direct-animal GHG production.

	CONV			ALT		
	Mean	Lower[3]	Upper[3]	Mean	Lower[3]	Upper[3]
Grazed area, m^2 per cow[1]	12100	12100	12100	10700	10700	10700
Days	177	177	177	84	84	84
C Sequestration						
C m^{-2} yr^{-1}, g[2]	282.0	241.0	323.0	138.0	95.0	181.0
CO_2 m^{-2} yr^{-1}, g	1034.1	883.8	1184.5	506.1	348.4	663.7
C $animal^{-1}yr^{-1}$, kg	3412.2	2916.1	3908.3	1476.6	1016.5	1936.7
CO_2e $animal^{-1}$, kg	12512.7	10693.4	14331.9	5414.7	3727.5	7101.9
CO_2e kg HCW cow exposed $^{-1}$, [3]	38.98	33.31	44.65	17.86	12.29	23.42
CO_2 from respiration m^{-2} yr^{-1}, [4]	281.5	218.2	387.2	145.1	127.8	162.4
C from respiration m^{-2} yr^{-1}	76.75	59.52	105.59	39.56	34.85	44.28
C Production[5]						
CO_2e per cow exposed						
CO_2e N_2O and CH4 from manure, burning of fossil fuels (CH_4 23x CO_2 and N_2O 298 x CO_2)[6]	2568.1	2568.1	2568.1	2425.6	2425.6	2425.6
CO_2e from CH_4 (23x CO_2)	3110.1	2590.8	3697.8	2734.3	2299.9	3169.5
CO_2e from CH_4 (4x CO_2)	540.9	450.6	643.1	475.5	400.0	551.2
CO_2e from CO_2	6610.3	5253.0	8039.4	5311.4	4535.3	5891.1
CO_2e N_2O and CH_4 from manure, burning of fossil fuels (CH_4 4x CO_2 and N_2O 235 x CO_2)	1874.7	1874.7	1874.7	1770.7	1770.7	1770.7
CO_2e per kg HCW per cow exposed						
CO_2e per kg HCW per cow exposed CH_4 only	1.68	1.40	2.00	1.57	1.32	1.82
CO_2e per kg HCW per cow exposed CO_2 only	20.59	16.36	25.04	17.52	14.96	19.43
CO_2e from per kg HCW from N_2O, manure, burning of fossil fuels	5.84	5.84	5.84	5.84	5.84	5.84
CO_2e per kg HCW Total, kg	28.12	23.61	32.89	24.93	22.12	27.09

[1] Cows monitored for GHG in CONV system stocked at 1.21 ha cow^{-1} rotationally grazed bromegrass pasture for 177 days. ALT cows allowed 1 ha cow^{-1} on oat forage grazed for 84 d.

[2] Net ecosystem exchange (NEE) over the entire year for CONV cows on pasture. For ALT cows NEE was determined over cover crop grazing period

[3] Carcass weight per cow exposed was 321 and 303 for CONV and ALT, respectively over years 1 and 2 of the study.

[4] Respiration from CO_2 from both cows and calves measured when cattle were in the footprint area of eddy covariance technique

[5] Total production of CO_2 from gestation, lactation, growing, and finishing phases in CONV and ALT systems

[6] Adapted from Beauchemin et al. (2010)

Table 3.9b. Carbon sequestration required to maintain carbon neutrality in pasture-based (CONV) or partial confinement (ALT) beef systems.

	CONV			ALT		
Required C sequestration[1]	Mean	Lower	Upper	Mean	Lower	Upper
CH_4 23x CO_2 and N_2O 298 x CO_2						
kg C per year	3351	2650	3712	2677	2347	2954
kg CO_2 per year	12289	9719	13612	9816	8606	10831
g per m^2 per year, g C	277	219	307	250	219	276
g per m^2 per year, g CO_2	1016	803	1125	917	804	1012
g per m^2 per day, g C	1.565	1.237	1.733	2.978	2.611	3.286
g per m^2 per day, g CO_2	5.738	4.538	6.356	10.922	9.575	12.051
CH_4 4x CO_2 and N_2O 234 x CO_2						
kg C per year	2461	2067	2879	2061	1829	2240
kg CO_2 per year	9026	7578	10557	7558	6706	8213
g per m^2 per year, g C	203	171	238	193	171	209
g per m^2 per year, g CO_2	746	626	872	706	627	768
g per m^2 per day, g C	1.149	0.965	1.344	2.293	2.035	2.492
g per m^2 per day, g CO_2	4.214	3.538	4.929	8.409	7.461	9.138
C $animal^{-1}yr^{-1}$, kg	2461.37	2066.60	2878.94	2060.98	1828.71	2239.68
CO_2e $animal^{-1}$, kg	9025.91	7578.31	10557.17	7557.67	6705.94	8213.00

[1] Calculated as the sequestration needed to make beef production from CONV or ALT system carbon neutral

Table 3.9c. Carbon balance pasture-based (CONV) or partial confinement (ALT) beef systems.

	CONV			ALT		
Net CO_2e after C sequestration[1]	Mean	Lower	Upper	Mean	Lower	Upper
CH_4 23x CO_2 and N_2O 298 x CO_2						
C m^{-2} yr^{-1}, g	5.1	31.0	-6.8	-112.2	-119.3	-116.0
CO_2 m^{-2} yr^{-1}, g	18.5	113.6	-24.8	-411.4	-437.6	-425.5
C $animal^{-1}yr^{-1}$, kg	61.1	374.8	-82.0	-1200.4	-1276.8	-1241.7
CO_2e $animal^{-1}$, kg	224.1	1374.3	-300.5	-4401.7	-4682.2	-4553.3
CO_2e kg HCW^{-1} per cow exposed $^{-1}$	0.7	2.1	-3.1	-16.7	-17.6	-17.2
CH_4 4x CO_2 and N_2O 234 x CO_2						
C m^{-2} yr^{-1}, g	78.6	79.2	62.1	-54.6	-70.9	-49.3
CO_2 m^{-2} yr^{-1}, g	288.2	290.5	227.6	-200.3	-260.0	-180.8
C $animal^{-1}yr^{-1}$, kg	950.8	958.4	751.1	-584.4	-758.7	-527.7
CO_2e $animal^{-1}$, kg	3486.7	3514.5	2754.2	-2142.9	-2782.2	-1935.0
CO_2e kg HCW^{-1} per cow exposed $^{-1}$	10.9	10.9	8.6	-7.1	-9.2	-6.4

[1] Net balance after subtracting emissions from actual sequestration

Table 3.10. Sources of CH_4, CO_2, and N_2O in phase of pasture-based (CONV) or partial confinement (ALT) beef systems.

	CONV					ALT				
System balance	% of Sequestration	CH_4	CO_2	N_2O	Total	% of Sequestration	CH_4	CO_2	N_2O	Total
Gestation										
days	16.14%	188				32.42%	183			
CO_2e kg^{-1} CW cow exposed		0.5	4.4	1.5	6.3		0.4	3.9	1.5	5.8
CO_2e g $animal^{-1}$ d^{-1}		0.8	23.2	2.5	26.5		0.6	62.6	2.6	65.8
CO_2e animal total, kg		153.1	1398.1	468.7	2019.8		113.2	1173.8	468.7	1755.7
Lactation										
days	32.94%	177.0				50.92%	182.0			
CO_2e kg^{-1} CW cow exposed		0.8	10.6	1.5	12.8		0.2	7.4	1.5	9.1
CO_2e $animal^{-1}$ d^{-1}		1.4	19.2	2.6	23.3		0.3	12.3	2.6	15.1
CO_2e animal total, kg		247.4	3405.6	468.7	4121.7		47.7	2240.8	468.7	2757.1
Growing										
days	9.71%	116.0				20.97%	116.0			
CO_2e kg^{-1} CW cow exposed		0.2	2.1	1.5	3.8		0.2	2.0	1.5	3.7
CO_2e $animal^{-1}$ d^{-1}		0.6	115.3	4.0	120.0		0.5	98.8	4.0	103.4
CO_2e animal total, kg		66.8	679.5	468.7	1214.9		63.5	603.3	468.7	1135.4
Finishing										
days	13.34%	148.0				34.54%	183.0			

CO$_2$e kg^{-1} CW cow exposed		0.2	3.5	1.5	5.2		0.4	4.3	1.5	6.2
CO$_2$e animal^{-1} d^{-1}		0.5	7.6	3.2	11.3		0.6	7.1	2.6	10.2
CO$_2$e animal total, kg		73.7	1127.2	468.7	1669.5		108.0	1293.6	468.7	1870.3
	Sequestration	Production	% of sequestered C remaining			Sequestration	Production	% of sequestered C remaining		
C animal^{-1} yr $^{-1}$, kg	3412.2	2461.35	27.87%			1476.6	2050.29	-38.85%		
CO$_2$e yr^{-1}, kg	12512.7	9025.9				5414.7	7518.5			
CO$_2$e kg cow exposed	39.0	28.12				16.9	24.80			
CO$_2$e animal^{-1} d^{-1}		14.3					11.3			
CO$_2$e animal total, kg										

FIGURES

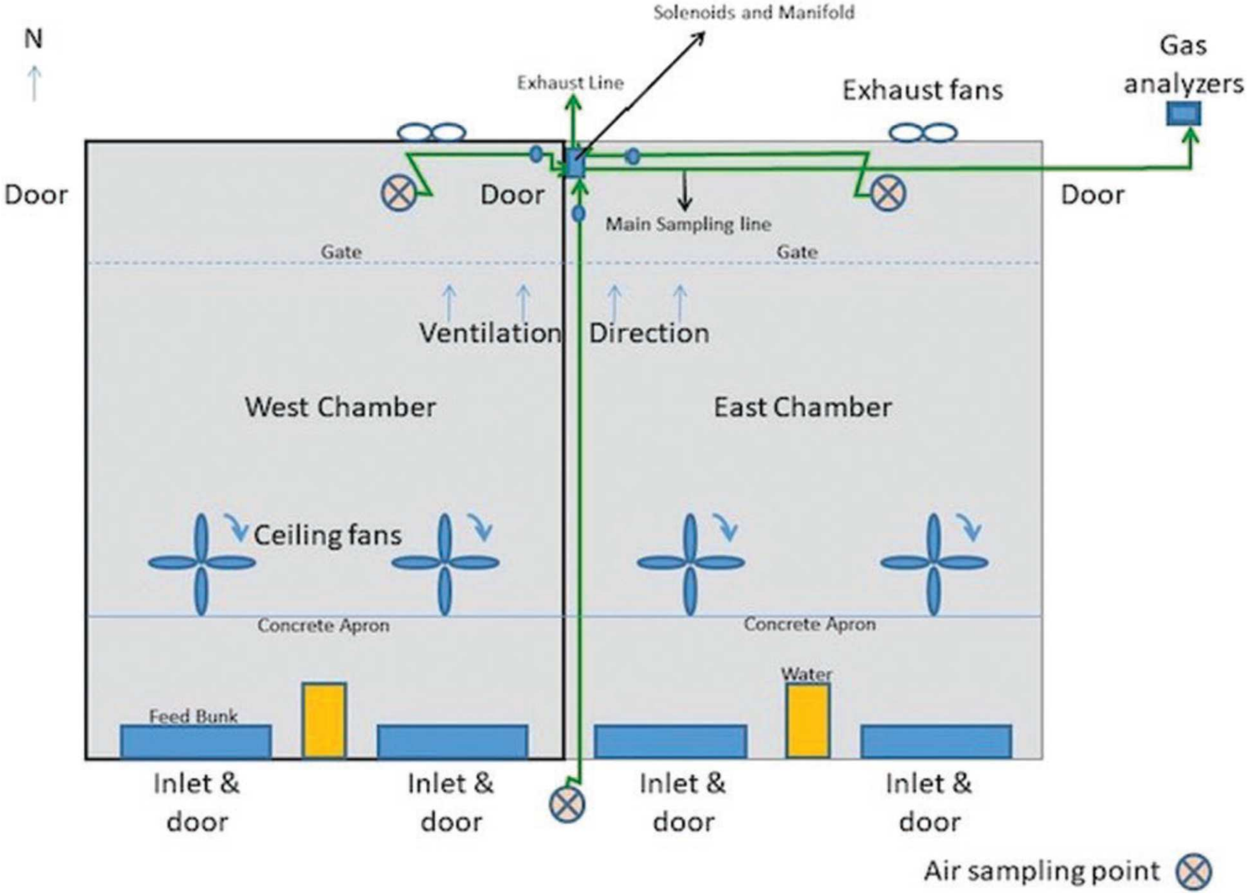


Figure 3.1. Large pen chamber layout. Side by side chamber used to measure CH4 and CO2 in lactating and gestating cows in ALT system and all calves during growing and finishing period post weaning.

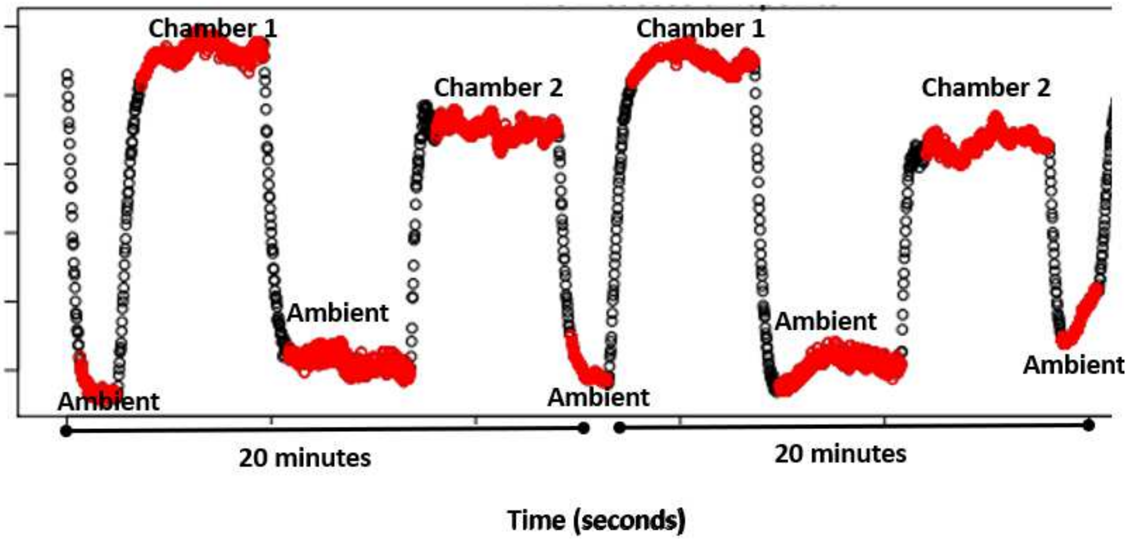


Figure 3.2. Output from statistical software (R Foundation, Indianapolis, IN) of data from large pen chamber. Data highlighted in red was used to calculate the average CH_4 and CO_2 concentrations during each chamber and ambient air samplings. Two 20-minute cycles of CH_4 are shown. The difference in mean concentration of air samplings for each side of the pen chamber was used to calculate CH_4 and CO_2 production animal^{-1} day^{-1}.

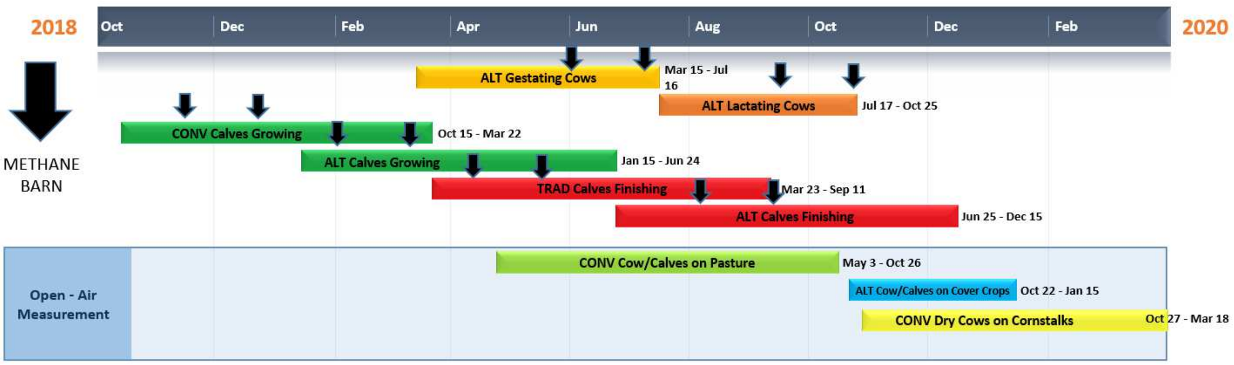
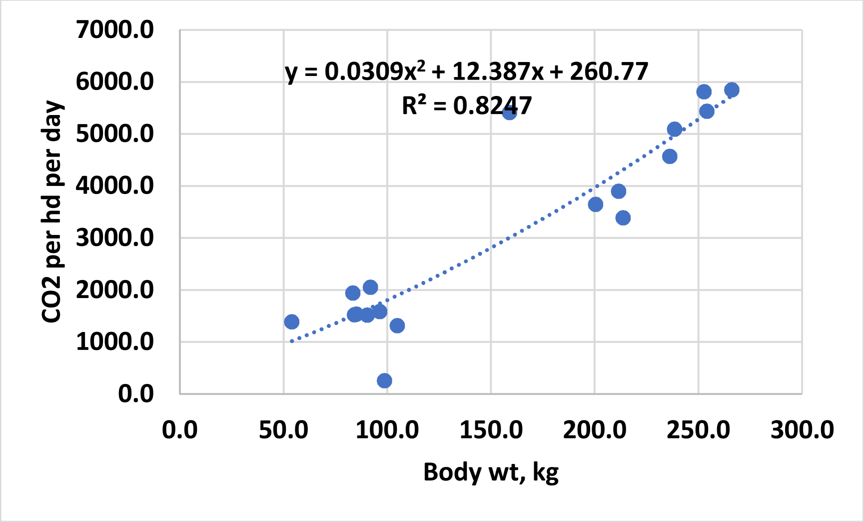


Figure 3.3. Yearly cycle of all GHG measurements in both CONV and ALT systems for pre weaning and post weaning periods. Start and end of methane barn measurements marked by black down arrows. All GHG monitoring during grazing period was continuous.



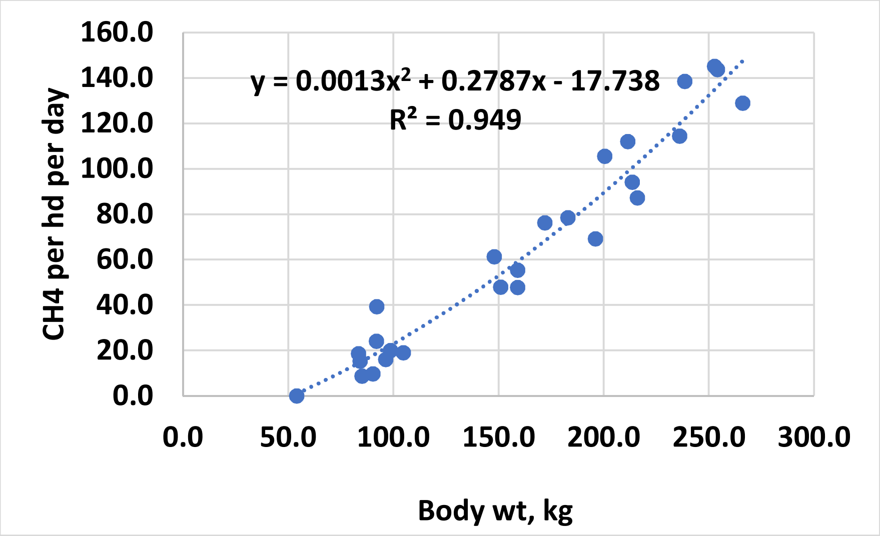


Figure 3.4. Regression analysis of calf CH_4 and CO_2 production from birth to shortly after weaning. Data from calves measured in the pen chamber removed from cows for 6 h, Holstein calf data from Stackhouse et al (2011), Holstein heifer data from Ramirez-Restrepo et al. (2015).

CO_2 production g animal^{-1} day^{-1} = 0.0309(BW, kg)^2 +12.387(BW, kg) +360.77. R^2=0.8247

CH_4 production animal^{-1} day^{-1} = 0.0013(BW, kg)^2 + .2787(BW, kg) -17.738 R^2 = 0.949

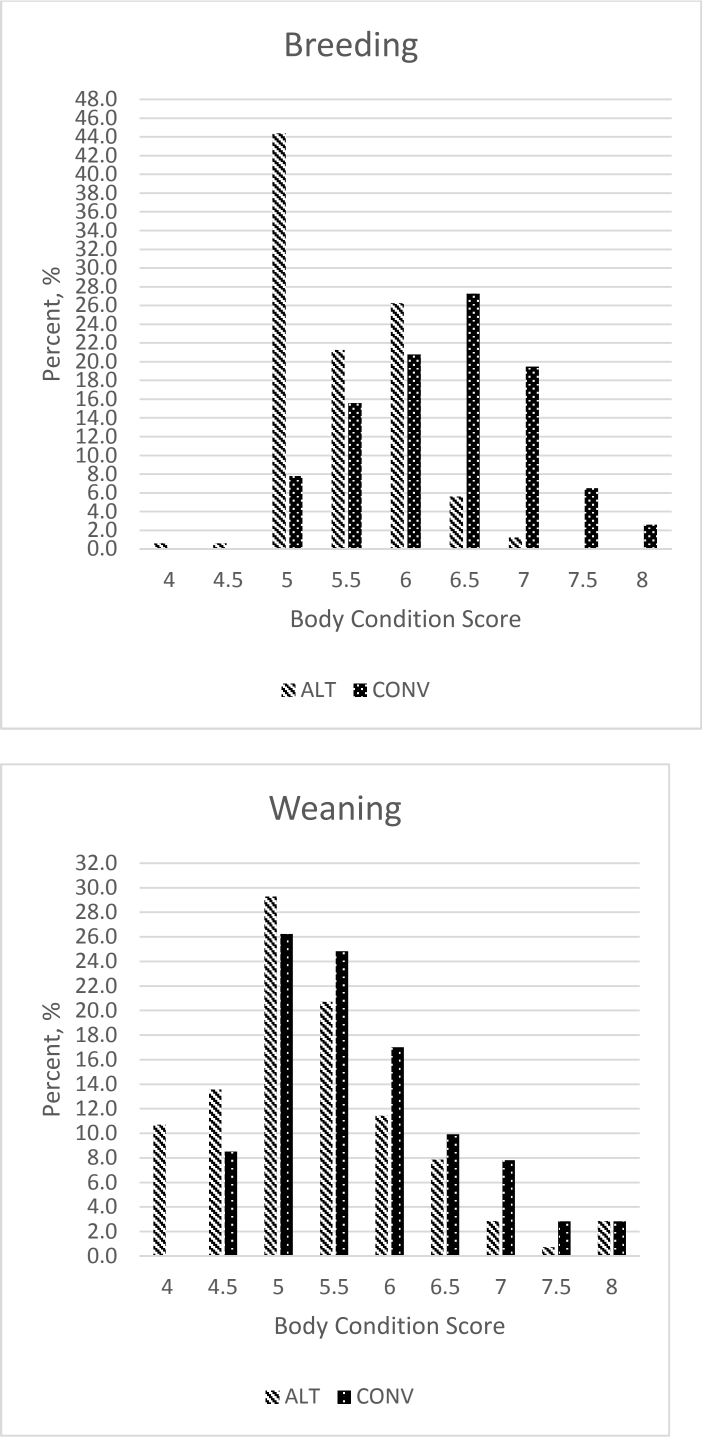


Figure 3.5. Cow body condition score (BCS) at weaning and the start of breeding season. Cow BCS was, on average, lower in ALT calves. However, little change occurred between years 1 and 2 indicating BCS was unchanging across time.

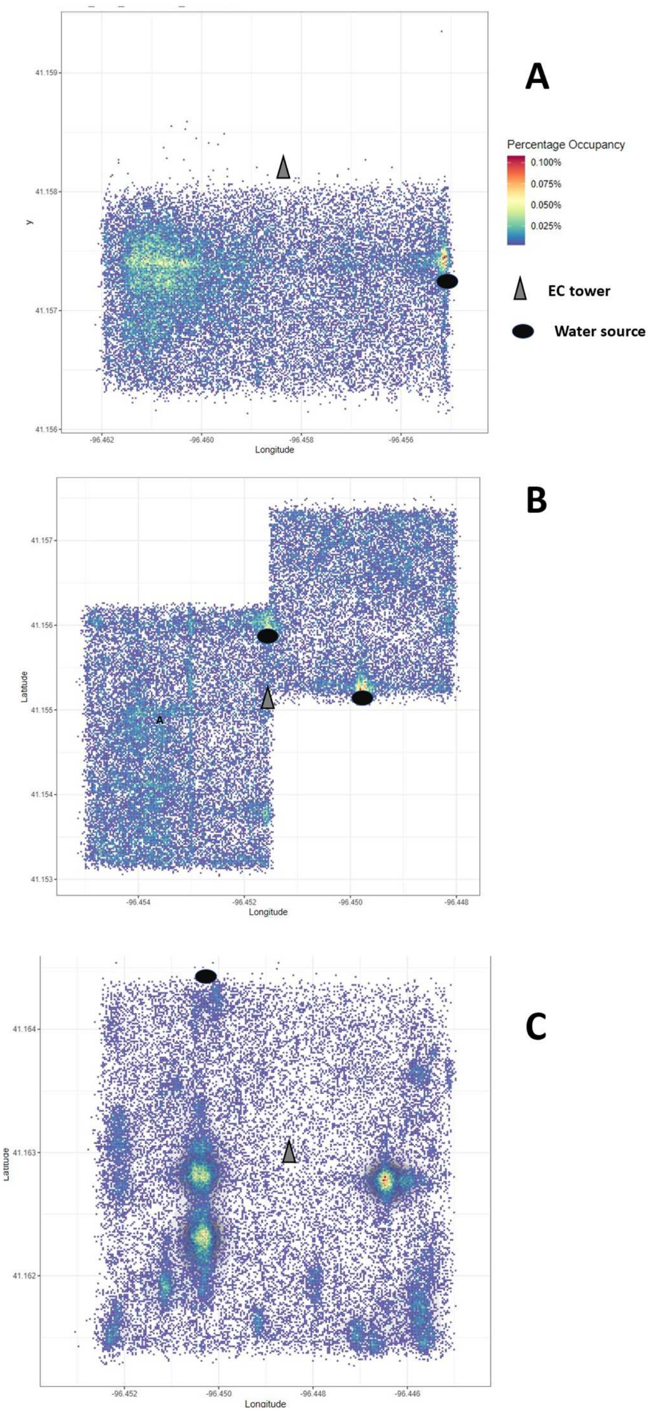
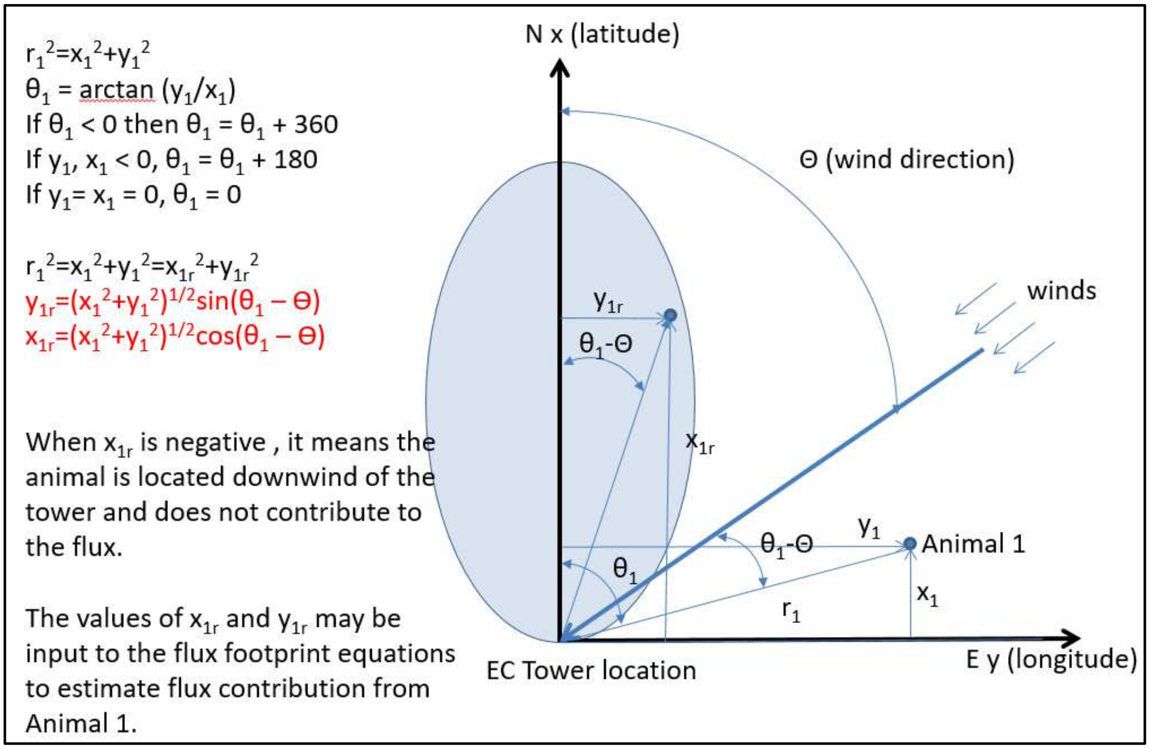


Figure 3.6. Animal grazing distribution for (A) forage oat grazing (10/28/20 to 11/27/20), (B) bromegrass grazing (07/17/20 to 8/21/20) and (C) corn residue grazing 12/6/20 to 2/11/20. Eddy covariance tower shown by gray triangle and water drinking founts in black ovals.



$r_1^2=x_1^2+y_1^2$

$\theta_1 = \arctan(y_1/x_1)$

If $\theta_1 < 0$ then $\theta_1 = \theta_1 + 360$

If $y_1, x_1 < 0, \theta_1 = \theta_1 + 180$

If $y_1 = x_1 = 0, \theta_1 = 0$

$r_1^2=x_1^2+y_1^2=x_{1r}^2+y_{1r}^2$

$y_{1r}=(x_1^2+y_1^2)^{1/2}\sin(\theta_1 - \Theta)$

$x_{1r}=(x_1^2+y_1^2)^{1/2}\cos(\theta_1 - \Theta)$

When x_{1r} is negative , it means the animal is located downwind of the tower and does not contribute to the flux.

The values of x_{1r} and y_{1r} may be input to the flux footprint equations to estimate flux contribution from Animal 1.

Figure 3.7. Diagram of adjustment of GPS coordinates to an x-y plane. Coordinates are rotated to coincide with wind direction and flux footprint area. These coordinates are used to determine the absence or presence of animals in the footprint area.

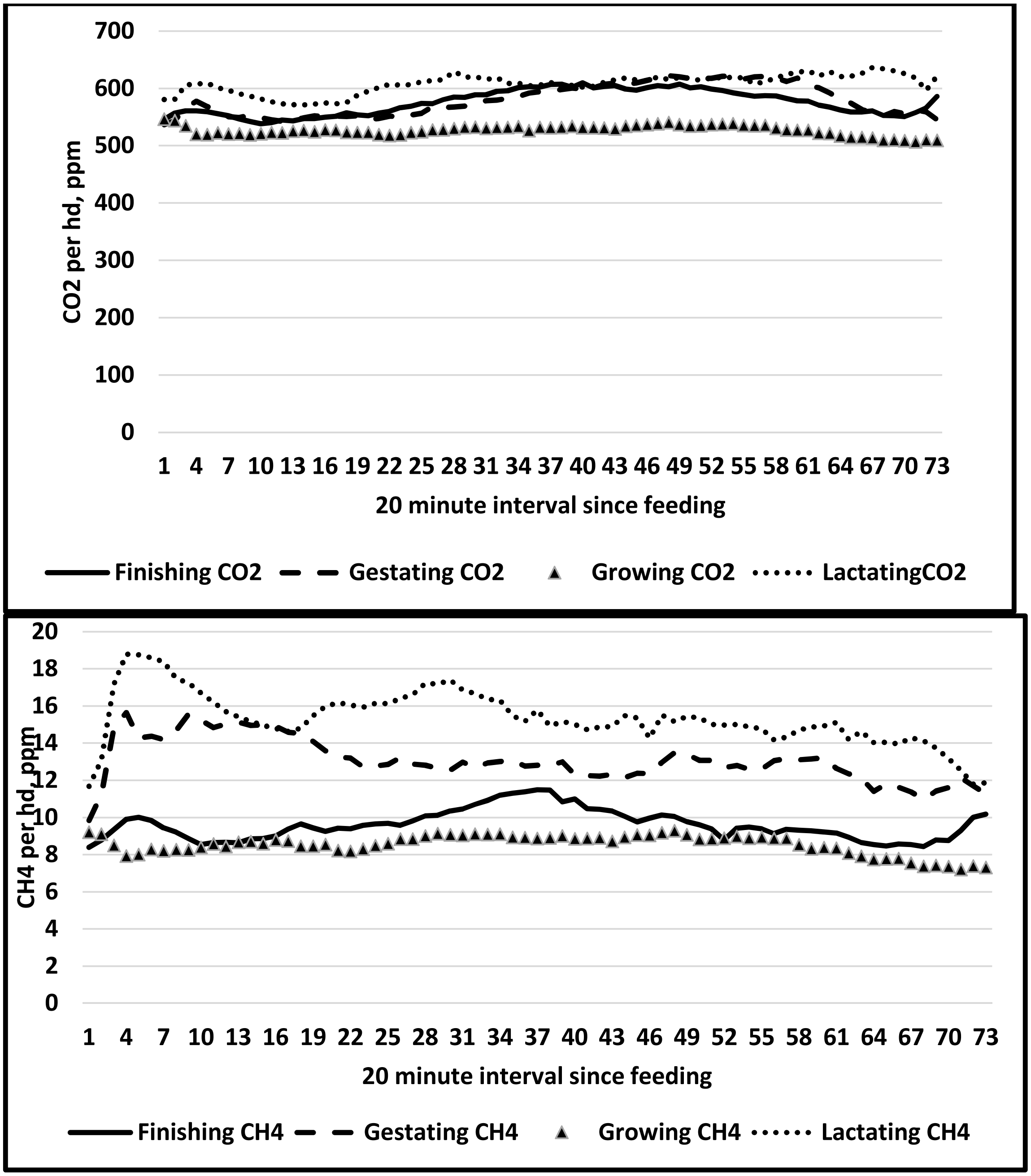


Figure 3.8. Concentration of methane (CH_4) and carbon dioxide (CO_2) in the pen chamber for gestating and lactating cows and calves post weaning during growing and finishing phases. Time is expressed as 20 minute interval since feeding. Concentration of CO_2 and CH_4 is expressed as barn ambient air concentration divided by animals present. Clear spike for both cow measurements since they were limit fed and typically consumed all feed within 4 hours of feeding time. Growing and finishing calves were given ad libitum access to feed.

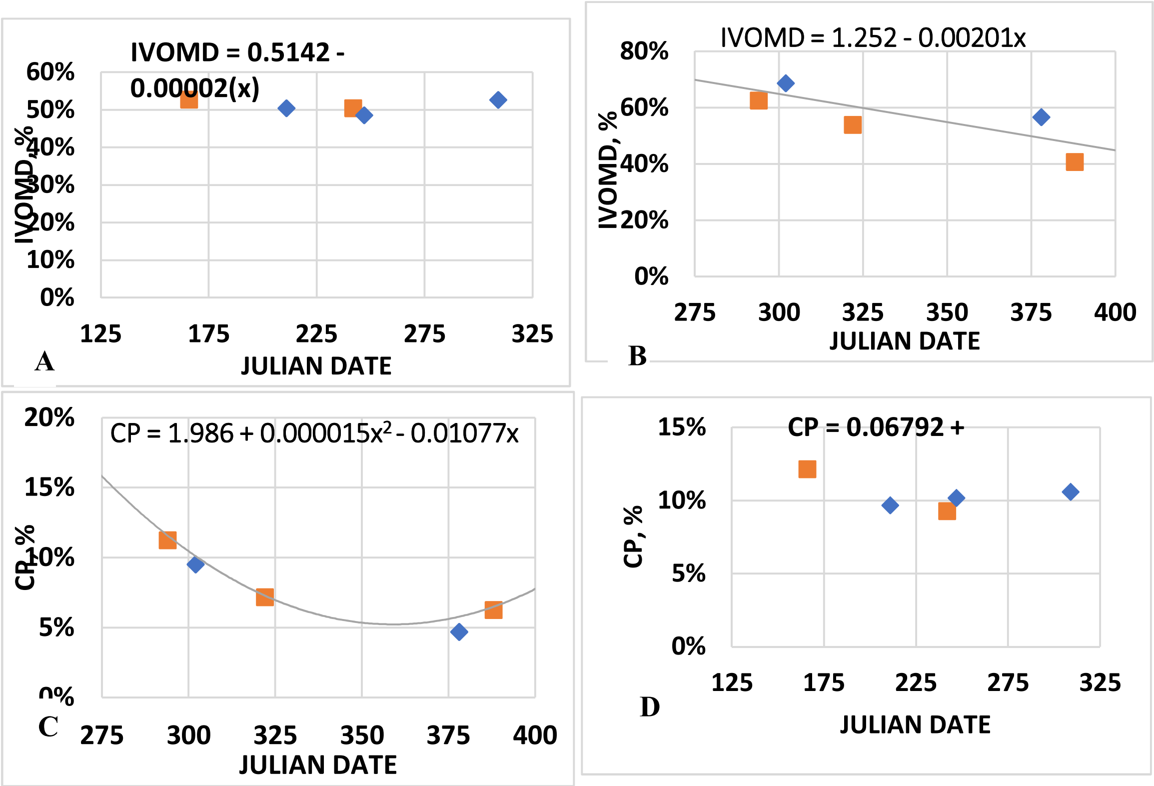


Figure 3.9. In vitro organic matter digestibility (IVOMD) and crude protein (CP) levels for smooth bromegrass pasture (A and B) and grazed forage oat (C and D). Values from the year 1 (blue diamonds) and year 2 (orange square) are shown. A values decreased linearly over time and C showed a quadratic change in IVOMD over time. No linear or quadratic relationship in B or D, therefore no season-long change in IVOMD or CP.

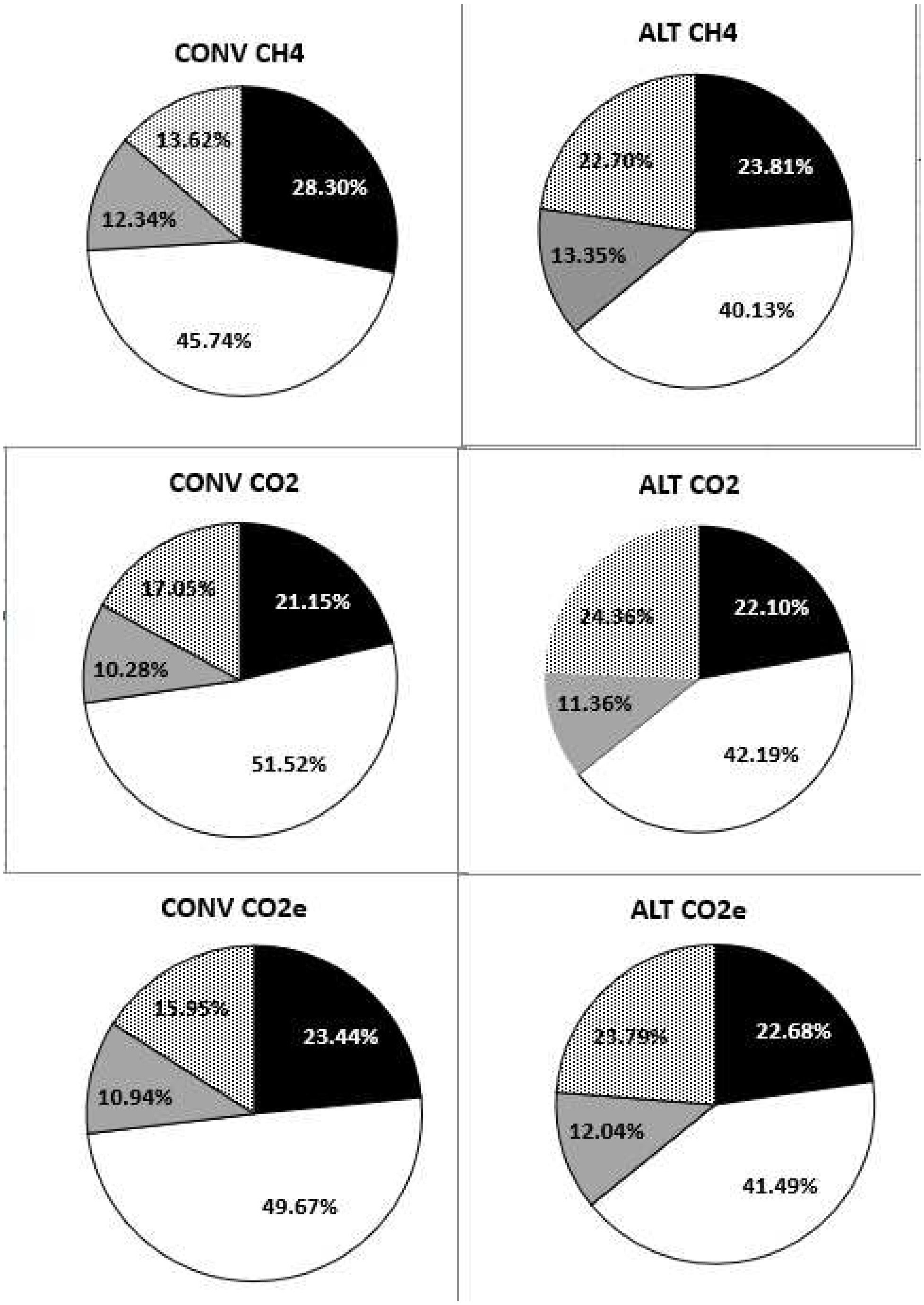


Figure 3.10. Relative contribution of CO_2e from enteric methane production and CO_2 from respiration for both CONV and ALT systems during gestation (black), lactation (white), growing (gray) and finishing (pattern) phases. GWP of CH_4 is 4.

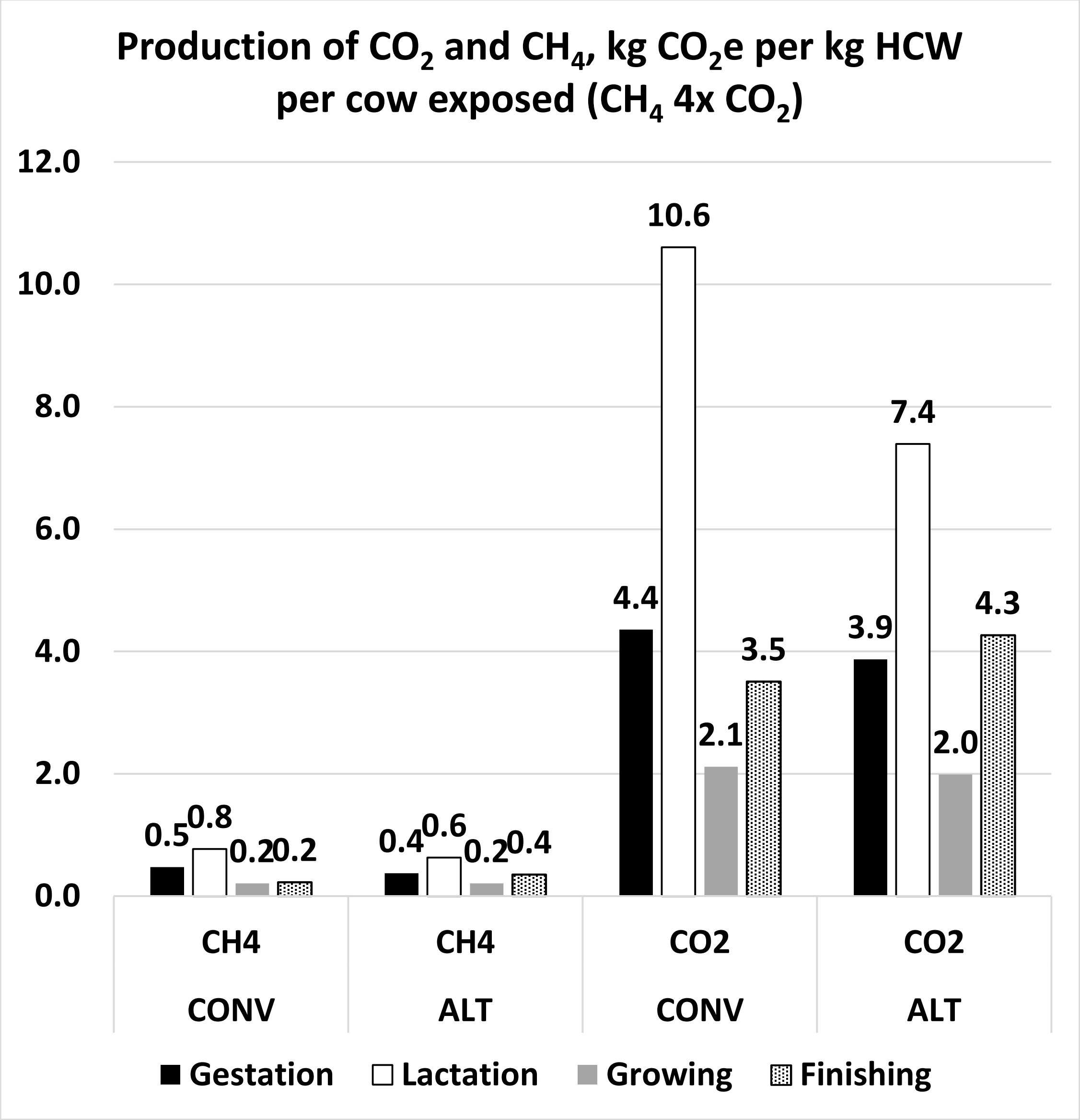


Figure 3.11. Production of enteric methane and CO2 from respiration in kg^{-1} CW per cow exposed during gestation, lactation, growing and finishing stages of production.

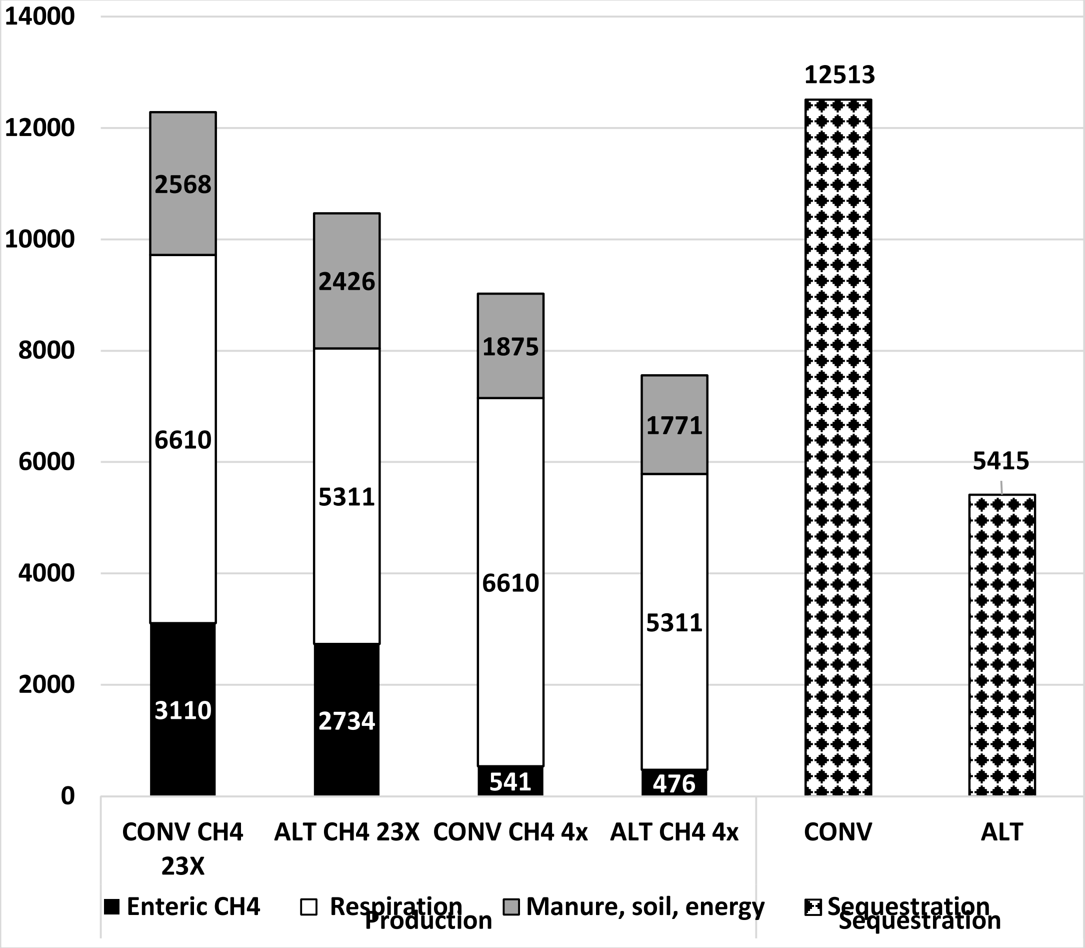


Figure 3.12. Production of enteric methane (CH4) and carbon dioxide (CO2) from pasture-based production system (CONV) and partial-confinement system (ALT). Emissions present with CH4 and N2O GWP of 4 and 235 or 23 and 295, respectivelyl. Manure, soil, and energy N2O, CH4, and CO2 modeled from Beauchemin et al. (2010). Sequestration from the CONV system is enough to remove all CO2e from all 4 stages of beef production whether expressed with traditional or new GWP of gases.

APPENDIX

MATERIALS AND METHODS

Water is the first limiting nutrient and water use in the food production system has come under increased scrutiny. Direct water intake by cattle accounts for only 3% of water use in the beef production system while the other needs are primarily used in the production of feed for cattle. Changes in animal performance and efficiency can decrease water consumption needs and water used for feed production (Capper 2012, White and Capper 2013, White et al. 2015). In addition, evapotranspiration (ET), the water transferred to the atmosphere by soil evaporation and plant transpiration, will be measured in grazing scenarios to estimate the water needed for forage growth. Previous estimates of maize (Udom and Kamalu 2019) and pasture (Murphy, Lodge, and Harden 2004) ET and its effect on herbage mass and use as a predictor for irrigation timing. This method will be used to measure water us in beef production systems.

Feed and Forage Sample Collection and Analysis

Ingredients from gestation, lactation, growing and finishing diets were collected weekly, weighed, and dried using a forced air oven at 60°C (AOAC 1999; method 934.01). Dried samples were ground through a Wiley mill (Model 4 Thomas Scientific, Swedesboro, NJ) and composited by month. Ash and OM were measured by putting 0.5 g of each feed ingredient in a muffle furnace for 6 h at 600°C (AOC, 1999, method 945.05). Neutral and acid detergent fiber (NDF and ADF) analysis were conducted using the procedures by ANKOM Technologies (2017). Feed refusals were weighed, sampled and frozen before being analyzed for DM which was done in the same manner of all weekly samples. Crude protein (CP) was analyzed using a combustion-type N analyzers (FlashSmart N/Protein Analyzer CE Elantech, Inc., Lakewood, NJ).

To sample the nutritive value of grazed forages (bromegrass and oat forage) two ruminally cannulated steers had their rumens evacuated of all contents at 0800. Cattle were then put on each paddock or pasture and allowed to graze for 30 min. Once grazing was complete, cannulated steers were returned to the squeeze and masticate samples were collected and put on ice before rumen contents were put back in the rumen and samples taken to the lab. Samples were frozen at -4ºC until lypholized at -50ºC (Virtis Freezemobile 25ES, Life Scientific Inc., St. Louis, MO) and then ground through a 1-mm screen using a Wiley mill (Model 4; Thomas Scientific). Freeze dried samples were analyzed for corrected dry matter. In vitro organic matter digestibility (IVOMD) was determined for 48 h using the method described by Tilley and Terry (1963). The Tilley and Terry (1963) method was modified by adding urea to McDougall's buffer (McDougall, 1948) at a rate of 1 g urea/L of buffer solution to ensure rumen microbes had adequate N in rumen fluid (Weiss 1994). Any IVOMD was completed using rumen fluid from 2 steers being fed a diet of 70% bromegrass hay and 30% distillers grains. Two replications per sample were completed. Once 48h incubation was complete samples were filtered using filter paper with particle filtration of 22um (Whatman Grade 541; Cytiva, Marlborough, MA) and dried at 100ºC to determine DM disappearance. Samples were then placed in crucibles and dried in a muffle furnace at 600ºC to determine OM disappearance. To adjust for any feed particles from inoculum, blanks were included in each *in vitro* run. Five grass hay standards with known *in vivo* (total tract) digestibility (51-60% range) were used to adjust IVOMD values (Stalker et al., 2013). After adjustments, IVOMD were decreased -0.00581 percentage units. This process was repeated early, mid, and late in the grazing season of each year for bromegrass pasture and oat forage.

Literature values were used for IVOMD of grazed corn residue. Cattle are selective grazers when utilizing corn residue. Leaf and husk account for 65- 72% of utilized residue (Fernandez-Rivera and Klopfenstein 1989). Corn residue on average is 11.2, 9.1, 40.7, 39.0 % DM grain, cobs, stalks and husks-leaves (Lamm and Ward, 1981). In vitro DMD considered to be 98.6, 64.8, 42, 41 and 48.1 for grain, husks, leaf blades, stems and cobs (Gutierrez-Ornelas and Klopfenstein 1991) Using combined data from Lamm and Ward (1981) and Gutierrez-Ornelas and T. J. Klopfenstein (1991), a weighted average IVOMD was calculated (49.8%) and compared to values in Burken (2014) who showed that IVOMD decreased over the winter grazing period.

Estimation of DMI in grazed scenarios based on estimated % GE loss from methane

To calculate C balance, a measure or estimate of C intake is needed. Nutrient profiles of cow drylot diets and grazed forages are found in Tables A1 and A2, respectively. In the pen chamber, DMI was directly measured. Measuring or estimating intake of grazed forages is difficult. Existing methods use chromium marker to estimate intake of forages with known digestibility or using NE equations from the beef NRC model (1996) (MacDonald et al. 2007). Others have correlated gas production and nylon bag degradability with feed intake (0.88) digestible dry matter intake (0.93) and growth rate (0.95) (Blu and Ørskov 1993). To have reasonable estimates of feed intake in grazing scenarios, CH_4 production animal^{-1} d^{-1} was used to calculate GE loss. Based on predicted GE losses of forages in the NASEM (2016), GE intake was the used to calculate predicted DMI. Using total CH_4 production animal^{-1} d^{-1} (g) GE loss was calculated assuming 55.65 MJ/kg CH_4 and 4.18 MJ/Mcal. These estimated intakes were used to estimate C balance of cattle in each grazing scenario within the systems. For grazing corn residue the same CH_4 production is used for both ALT and CONV cows, 192 g animal^{-1} d^{-1}. This calculates to 2.55 Mcal GE lost due to CH_4. Book values for cornstalks estimate GE loss to be 5.4 to 12.1% with an average of 7.32%. Using the average GE loss from the NASEM 2016 model, calculated DMI on cornstalks is 8.9 kg. Using the equations from MacDonald et al. (2007), forage intake with protein supplementation is estimated at 18 g forage per kg BW. Cow BW of 590 kg calculate to 10.6 kg DMI. Given the level of error and variation in GHG production, this results in wide ranges in dependent variable values from model figures. Using this same method DMI on the early, mid and late grazing periods on grass, cow intakes are estimated to be 14.2, 16.7, and 11.2 kg DMI, respectively. On oat forage intakes over the entire period are estimated to be 23.2 kg DMI.

Carbon balance – intake

For smooth brome pasture and oat forage, gestating and lactating diet OM and TDN values were equal to NASEM 2016 standard values from feeds used. Calf intake assumed to be only milk in ALT calves during lactation since calves had limited intake of feed from the bunk due to limited bunk space. In CONV calves, calf intake assumed to be milk intake and DMI from feed. Abdelsamei et al. (2005) fed Holstein calves different levels of bottle-fed milk and measured *ad libitum* intake of alfalfa. The modeled amount of milk production for CONV and ALT herd based on 205 d adjusted weaning weight was 14.1 and 7.1 kg, respectively. The closest milk intakes in Adelsamei et al. (2005)

were a 13.66 kg for CONV average of 5.44 and 8.16 kg milk for ALT. Average alfalfa intakes for these treatments in Abdelsame et al. (2005) was 1.04 and 1.66 kg dry feed intake, respectively. These were the assumed dry feed intakes in the pasture and oat forage grazing scenarios, and TDN and OM values for calf feed intake were assumed to be equal to the cow diet during that period.

To estimate C intake, the C content of the gestation and lactation diets was calculated given NASEM (2016) values for fat, carbohydrate, and measured values of crude protein (CP). These were used to calculate C content. Brome pasture, oat forage, and cornstalk C content was calculated in the same manner using measured brome and forage oat CP content, and book values for fat and carbohydrate. Average C content of feed OM was calculated from percent fat (70% C), protein (43% C), and carbohydrate (40% C). These were considered average molecular proportion of fat, protein, and carbohydrate, respectively.

Carbon balance – Feces, urine, milk, CH_4 and CO_2

Milk yield was estimated using calf weaning weights (WW). Mulliniks et al. (2020) estimated calf WW from milk production. Using milk production and WW data from 14 studies, WW (kg) = 7.8944 (Milk production, kg) + 164.18. The actual WW at 168 days of age in these systems were 229 and 184 for CONV and ALT, respectively. Assuming constant gain, these values adjusted to weaning at 205 days of age would be 276 and 220 kg. The values which are most consistent with these weaning weights according to Mulliniks et al. (2020) would be milk production of 14.2 and 7.1 kg for CONV and ALT, respectively. Milk C = Estimated milk yield, kg x ((% milk fat x 73% C) + (% lactose x 40% C) (% milk protein x 43% C)).

Daily emission values from calves (based on BW) and measured values from cows were used to calculate C loss from CO_2 (27.27% C) and CH_4 (74.78% C) based on molecular weight. Carbon loss from feces and urine was 1 - % TDN. Feed TDN values are well documented in both grazed and harvested feeds, but OMD values are not. Olson et. al. (2014) described the relationship between TDN and OMD in grazed forages. While TDN is a measurement of energy metabolism, its high correlation with OMD in grazed forages makes it a good proxy for estimated feed digestibility.

Some consideration must be made for mid-forage and low forage diets containing corn by product. Using TDN can also be used as a predictor for OMD in growing and finishing diets. Hamilton et al. (2017) tested corn by-products (distillers grains, distillers solubles, or wet corn gluten feed (Sweet Bran)) and their effect on the relationship of TDN and OMD. In all diets in the system DG or Sweet Bran (a wet corn gluten feed product) were fed to cows and calves in confinement. In both low and high forage diets, OMD was less than TDN between 3.58 to 11.1 pts, depending on level and type of by-product. In theory, DE content in by-products is greater due to higher fat and protein levels. Some of this could be due to the greater C values of protein (42%) and fat (70%) relative to carbohydrate (40%). This phenomenon will be taken into consideration when determining C balance.

Loss of C from feed for calves that consumed feed during brome pasture and oat forage was calculated assuming the same TDN as cow feed intake. This indigestible fraction of OM was assumed to have the same C concentration as feed. Assuming milk digestibility of 95% (Diaz et al., 2000) and C loss in feces was 5% of OMI from milk.

Carbon balance – calf, conceptus, and cow retention

Cow body condition scores (BCS) were taken on each system at weaning and at bull turnout during the breeding season. A histogram of each system is shown in Figure 4. While BCS, on average, was lower in ALT herd cows, BCS was consistent from year to year within system. As a result, for this exercise in calculating C balance it is assumed that net C retention in each cow is zero.

C retention was calculated from the estimated C content over all stages of production. The following equations were adapted from NASEM 2016:

Empty body weight:

$EBW_{conceptus} = \text{Birth weight (kg)}*(0.891)$

$EBW_{weaning} = \text{Weaning weight}*(0.891)$

$\text{Body Protein, kg} = 0.235(EBW) – 0.00013(EBW)^3 – 2.418$

$\text{Body Fat, kg} = 0.037(EBW) + 0.00054(EBW)^2 -0.610$

Carbon retention during gestation was calculated as the average growth of the conceptus per day. Carbon retained in conceptus was estimated from conceptus EBW and body protein and fat content. Birth BW (40 and 39 kg, for CONV and ALT respectively) was used to determine EBW, and C deposition per day averaged over 280 days of gestation. The percent C retained in calf growth was calculated based on birth to weaning ADG (0.88 and 1.19 kg for ALT and CONV, respectively) and estimated C content from fat and protein content in EBW. This body protein and fat composition changed with growth and was different at a given day of age because of lower growth in ALT calves relative to CONV. To estimate C retention from conceptus and calf growth the following equation was used: Body C retention per day, g = (kg fat x 70%) + (kg protein x 43%) x 1000 / days of gestation (280) or days of age at weaning (168).

Carbon balance

The calculated values from C intake, C retention, and fecal loss were combined with measured values of CO_2 and CH_4 loss to calculate C balance:

$$\text{C balance, \%} = 100 \text{ x } \frac{(\text{C intake-C feces and urine-C CH4 - C-CO2 C-C retained in calf or conceptus-C milk})}{\text{C intake}}$$

Given the nature of compounding errors, the C balance values will be used to determine the approximate fates of C intake but substantial variation in each measure will make comparisons between environments and physiological states impossible.

Water Intake

Water intake was measured at all segments of production except CONV cows fed grass hay from March 16 to April 30th. This was modeled data from Wagner and Engle (2021) for mature cows wintered between 4 and 10°C. In the feedlot pens during growing and finishing periods, water intake was measured with water meters on incoming water lines (Neptune T10, Neptune Technology Group, Tallassee, AL). Calves from 2 replications of each system shared one water tank (J360, Johnson Concrete Products, Hastings, NE) so the experimental unit was water tank, not pen. The same procedure was done for the cows fed in confinement.

Water intake of cows and calves on brome grass was measured at the same site where EC measurements were conducted. Three water tanks on the pasture were all fitted with water meters (Model M, Dalia, Israel, ARAD Water Measuring Technologies). Average intake was determined from total water measured from all 3 tanks. A 3 inch water meter (Manifold Flow Meter 3 inch, Banjo Liquid Handling Products, Crawfordsville, IN) was used to measure water delivered from a delivery truck for one replicate of CONV cows grazing corn residue and one replicate of ALT cows/calves grazing forage oats. Water intake from feed was calculated using of as-fed and dry matter fed in growing, finishing, and ALT cows fed in confinement. For grazed oat forage and bromegrass pasture, standing forage moisture content was assumed to be 80% (Rotz 1995). Daily mean, low, and high temperatures and precipitation data are reported from the National Weather Service (weather.gov) for Wahoo, NE.

Eddy Covariance

The following equations are utilized for the model:

$$A = \frac{1}{z_m}\left(1 - \frac{z_m}{h}\right)\left(\frac{\bar{u}(z_m)}{u_*}k\right)^{-1}$$

$$x^* = Ax_r$$

$$\overline{f^y} = AF^{y*}$$

$$\hat{F}^{y*} = a\left(\hat{X}^* - d\right)^b exp\left(\frac{-c}{\hat{X}^* - d}\right)$$

$$\hat{F}^{y*} = 1.4524\left(\hat{X}^* - 0.1359\right)^{-1.9914} exp\left(\frac{-1.4622}{\hat{X}^* - 0.1359}\right)$$

$$\hat{F}^{y*} = 1.4524(Ax_r - 0.1359)^{-1.9914} exp\left(\frac{-1.4622}{Ax_r - 0.1359}\right)$$

$$\hat{F}^{y*} = \frac{\overline{f^y}}{A} = 1.4524(Ax_r - 0.1359)^{-1.9914}\, exp\left(\frac{-1.4622}{Ax_r - 0.1359}\right)$$

$$\hat{F}^{y*} = \frac{\overline{f^y}}{A} = \frac{\overline{f^y(x)}}{A} = 1.4524(Ax_r - 0.1359)^{-1.9914}\, exp\left(\frac{-1.4622}{Ax_r - 0.1359}\right)$$

$$\overline{f^y(x)} = 1.4524A(Ax_r - 0.1359)^{-1.9914}\, exp\left(\frac{-1.4622}{Ax_r - 0.1359}\right)$$

p_{s1} a function of stability depends of L:

For L $\leq 0 \quad C = \left|\frac{z_m}{L}\right| \times 10^{-5} + 0.80$

For L $> 0 \quad C = \left|\frac{z_m}{L}\right| \times 10^{-5} + 0.55$

$p_{s1} = min[1, C]$

Let B be

$\frac{z_m \sigma_v}{p_{s1} u_*}$

$$\sigma_y^* = p_{s1} \frac{\sigma_y \, u_*}{z_m \sigma_v}$$

$$\sigma_y = \sigma_y^* \, \frac{z_m \, \sigma_v}{p_{s1} u_*}$$

$$\sigma_y = \sigma_y^* \, B$$

$$\sigma_y^* = a_c \left(\frac{b_c\left(\hat{X}^*\right)^2}{1 + c_c \hat{X}^*}\right)^{\frac{1}{2}}$$

Rewrites as:

$$\hat{\sigma}_y^* = a_c {b_c}^{0.5} \hat{X}^* \left(1 + c_c \hat{X}^*\right)^{-0.5}$$

Since:

$$\hat{X}^* = Ax_r$$

We have:

$$\hat{\sigma}_y^* = a_c {b_c}^{0.5} Ax_r (1 + c_c Ax_r)^{-0.5}$$

$$a_c = 2.17\,;\ b_c = 1.66;\ c_c = 20.0$$

From the main equation we have:

$$f(x,y) = \overline{f_y}(x) \frac{1}{\sqrt{2\pi}\sigma_y} exp\left(-\frac{y^2}{2\sigma_y^2}\right)$$

$$f(x,y) = (2\pi)^{-0.5}\, \overline{f_y}(x)\, {\sigma_y}^{-1} exp\left(-0.5\, y^2\, {\sigma_y}^{-2}\right)$$

We replace σ_y and we have:

$$f(x,y) = (2\pi)^{-0.5}\, \overline{f_y(x)}\, \left(a_c {b_c}^{0.5} Ax_r (1 + c_c Ax_r)^{-0.5}\right)^{-1} \exp(-0.5{y_r}^2 \left(a_c {b_c}^{0.5} Ax_r (1 + c_c Ax_r)^{-0.5}\right)^{-2}$$

Replacing $\overline{f_y(x)}$ in the equation we have:

The density of methane is calculated to be 0.667 kg/m^3 when the prevailing air temperature is 20°C at 1 atmosphere or 1.013 bar.

Converting to kg per second we obtain:

$$1.667 * 10^{-5}\, m^3 s^{-1} * 0.667\, \frac{kg}{m^3} = 1.112 * \frac{10^{-5} kg}{s}$$

The molar mass of methane = 16.04 g/mol

$$1.112 * \frac{10^{-5} kg}{s} * 1000\ \frac{g}{kg} * \frac{1\ mol}{16.04 g} * \frac{10^{6} \mu mol}{mol} = 770.682 \frac{\mu mol}{s}$$

Assuming that the amount of methane gas emitted by each livestock is 105 L/min we can convert this amount to µmol/sec by multiplying by 770.7 to obtain 80,921.57$\frac{\mu mol}{s}$

The release rate (units: µmol/s) is then multiplied by the flux footprint factor (units: m^{-2}) for the animal or source and the values are presented in µmol/m^2/s

For our subsequent calculations, determining the density of CH_4 at the prevailing air temperature and pressure is conducted for each 30- minute average interval.

The variables that are necessary to calculate the flux footprint contribution include:

Variable	**Abbreviation Units**	**Description**
ustar	u*	Friction velocity [m/s]
H	H	Sensible heat (W/m^2)
Ta	Ta	Mean air temperature (°C)
zm	zm	Instrument height (m)
zo	zo	Momentum roughness height (m)
σ_v	σ_v	Standard Deviation of wind component (ms^{-1})

To calculate the flux footprint contribution, several constants were utilized. These included:

Variable	**Description**	**Value**
k	Von Karman constant	0.4
Cp	Specific heat capacity of dry air at constant pressure (J/kg K)	1005
g	Gravitational acceleration constant	9.81

Converting °C to K

$Ta_K = Ta + 273.15$

Density of air (kg/m^3)

$$\rho = 1.3079 - 0.0045 \times Ta$$

Monin Obukhov length (m) is calculated as:

$$L = \frac{-u_*^3 T_v}{kgQ_{v0}}$$

T_v is a reference virtual temperature or also referred here as rho

$$\rho = 1.3079 - 0.0045 \times Ta$$

Q_{v0} which is the kinematic virtual temperature flux at the surface is calculated as

$\frac{H}{C_p \times Ta_k}$

The new length scale z_u is calculated as:

$$z_u = z_m \left(ln \left(\frac{z_m}{z_o} \right) - 1 + \frac{z_o}{z_m} \right)$$

The similarity constants D and P are presented below and were derived by regression analysis of the relationship below:

$$\left(\frac{x}{|L|} \right) = \frac{-1}{k^2 \, ln\,(F/S_o)} D \left(\frac{z_u}{|L|} \right)^P$$

Condition	**D**	**P**
Unstable	0.28	0.59
Near Neutral and neutral	0.97	1
Stable	2.44	1.33

The threshold used to determine various atmospheric conditions is 0.04.

The stability is measured is as $\frac{z_u}{L}$. If this value is less than -0.04, the conditions are considered as unstable. If the stability is greater than 0.04, the conditions are considered stable. Conditions that are not met as described below, are considered near neutral and neutral (fulfilling the condition below):

abs($\frac{z_u}{L}$) < 0.04

RESULTS AND DISCUSSION

Individual animal carbon balance

Carbon balance in the gestation diet was within 47 g C (1.7%) (Table A3). Limit-fed cows in the ALT system during gestation, on average, lost 3.8, 60.0, ad 34.0% of C as CH_4, CO_2 and feces, and only 0.4% (12 g animal^{-1} d^{-1}) was estimated for retained conceptus growth. Lactating ALT cows fed in confinement lost 3.2, 39.7, 31.7 and 9.1% from C intake as cow CH_4, CO_2, feces and milk. For C in calf metabolism, 0.2, 9.3, 0.5 and 3.5% of C was shuttled to CH_4, CO_2, feces, and body retention. Each of these estimates are close to zero C balance (1.7 and 2.9% for gestating and lactating, respectively) since these had the least variation in C intake and closest estimates based on CH_4 and CO_2 losses and standard values to generate losses based on NASEM 2016.

Small positive C balances in the gestation and lactation diet feeding on ALT cows could be the result in discrepancies in OMD and TDN. Hamilton et al. (2017) showed diets containing distillers grains (DG) show divergence in TDN and OMD, resulting TDN values that are greater than OMD. Energy digestion in DG diets does not reflect OMD. In the current trial assuming TDN is equal to OMD may result in more C remaining from the balance of intake and loss. Actual measurement of OMD would have corrected this error, but overall balance is less than 3% in both diets.

In the grazed scenarios, more C was lost as CO_2 (4896 and 4264 g C for brome grass, and forage oat, respectively) in the cows given greater DMI by the lactating cows during razing. Both grazing scenarios with cows and calves have the greatest C balance (39.1 and 5.0% for brome pasture and oat forage, respectively). This may be due to any combination of errors in the calculations described. For cows grazing corn residue, C balance is negative (-17.1%) indicating cows on residue could be losing body condition. However, multiple studies indicate that dry cows need little or no supplementation (Warner et al., 2011). The negative balance calculated could be from an intake estimate that is too low. Methane production from consumption of residue in the NASEM 2016 is variable (5.4 to 12.1% of GE). The average value for GE loss used was 7.3% indicating a DMI of 8.9 kg. According to the NASEM 2016 model, cows similar to those in the TRAD and ALT system mid to late gestation would lose some body condition given this intake. This is not supported from the BCS data (Figure 4). The GE loss value should be lower which would drive up estimated intake, improving C balance.

Carbon dioxide is a measure of a heat production (Johnson 2000 and Reynolds 2000). In cattle, ME intake for maintenance is burned as heat production for metabolism. After maintenance requirements are met, 50% of the remaining ME intake is used for heat and the other 50% for growth (Johnson 2000). Maintenance requirements in grazing animals are higher because of the energy expenditure required to walk and graze (Lachica et al. 1999; Agnew and Yan, 2000). In the present study both bromegrass and oat forage grazing scenarios likely have greater CO_2 production and maintenance requirements than ALT cows measured in the pen chamber. In a similar experiment Gourlez et al. (2018) estimated C contribution from respiration CO_2 in using EC. Measured nighttime fluxes with and without cattle in the footprint were used to calculate total ecosystem respiration and ecosystem respiration. The difference between these two values was the calculated CO_2 from cows. This calculation showed 3.0 +- 0.8kg C LU^{-1} d^{-1} (11,001 +- 2934 g CO_2 $animal^{-1}d^{-1}$). For the total grazing period C from respiration was 208 and 230 g C m^{-2} yr^{-1}. Based on ingested biomass this was 2.5 kg C per LU d^{-1} (6.60 kg DMI assuming grazed forage content 41.6% C and 91.15% OM) (Gourlez de la Motte et al. 2018). Using a similar method Felber et al. (2016) estimated dairy cow CO_2 emissions to be 4.6 +- 1.6 kg C $animal^{-1}d^{-1}$ (16,868 g +-5,867 CO_2). Assuming average CO_2 production per pair of 11,427 and 20,286 g for grazing bromegrass and oat forage, respectively, brings CO_2 balance to 0%. Both of these values are within the 95% confidence interval measured by Gourlez de la Motte et al. (2018).

There are multiple sources of variation within the C balance calculation. Carbon loss from milk is greatly influenced by the 7.1 vs 14.2 kg estimated milk yield from ALT and CONV calves which is estimated from WW. Calf feed intake is also estimated based on Abdelsamei et al. (2005) and is a source of variation. In all cases the BCS is assumed to not change. There is indication that cow BW did not change year to year, but variation in BCS could occur post-partum and post weaning when cows lose condition for milk supply and then gain back condition post-weaning. Retention in calves and conceptus could vary, but combined account for less than 3.8% of total C. Carbon loss from cow and calf CO_2 and CH_4 is the most reliable estimate in this calculation since it was measured.

Water

Daily water intake (Tables A4 and A5) for growing calves averaged 43.1 and 30.4 L for CONV and ALT, respectively. Weather data during this period would explain higher WI for ALT since mean low and high temperatures were greater. The opposite was true in the finishing period. Shipping for CONV calves occurred in June and July and ALT calves were fed until late November and early January. Calves in the ALT system experienced more hot days in the finishing period and were on feed for 35 days longer making total water intake per animal only 249 L (0.6%) greater. Estimated intakes for growing and finishing cattle of this size and at observed temperatures would be 20 to 29 L and 39 to 53 L, respectively (Wagner and Engle, 2021). A major contributor to oat forage and bromegrass pasture intake was intake from feed (58.7 and 91.6 L pair^{-1} d^{-1}, respectively). The estimates could be in error since DMI was not measured but estimated from GE loss due to methane and assumption that all standing forage was assumed to be only 20% DM. Total WI kg CW per cow produced was 128.8 and 124.9 L kg^{-1} for CONV and ALT, respectively. During the growing phase those values are high relative to predicted., even after removing 36.9 L animal^{-1} d^{-1} from the overflow for the period of December 12th, 2020 to February 26, 2021. The assumption of overflow rate being equal to the difference of water use before and after vs during overflow use may have been false.

Carbon balance in cattle research

Corn production has depleted soil C due to excessive tilling and land use change (Lal et al., 1998). Evidence that no-till can increase soil C greater than manure application or conventional tillage techniques (Buyanovsky and Wagner 1998) and less sequestration from cover crops to increases due in subsequent plant respiration (Baker and Griffis 2005). Similar to trends in beef production, some of the most recent evidence shows the C footprint of ethanol production from corn has declined due to less fertilizer and energy use per unit of corn and ethanol produced and displaced 544 million tonnes of CO_2e (Lee et al., 2021). Net ecosystem exchange (NEE) of corn production across various practices is approximately 300 g C m^{-2} (Baker and Griffis 2005). The current study shows similar data based on NEE and trends in beef production. More intensely managed pastures can be a sink of C while simultaneously maintaining or increasing beef production.

The CO_2 data reported in this paper serves both to serve as an estimate of respiration of metabolism and brings context to the designation of both C intake in feed and C output through respiration. In theory, these two values in combination with physiological C outputs (feces, calf and conceptus growth, milk, and retention) should be in balance. Carbon dioxide production represents a significant portion of C loss (16.7 to 59.9% of intake) while CH_4 has a smaller proportion (3.2 to 4.9%). The variability in C loss in feces, milk and retention adds difficulty to C balance calculations if not directly measured. Carbon inputs and output data are a valuable tool when calculating C sequestration and subsequent C balance from a grazed ecosystem. It is important to note that any C loss in the form of CH_4 would likely have been let off as CO_2 after cellular respiration, resulting in less overall waste. The reduction in methanogen metabolism of C allows for the use of that C by other rumen microbes. Using the consideration for overall C balance in grazed scenarios using EC methods, more research and thought needs to be considered when considering C balance of cattle consuming harvested feeds in open-lot pens. Recent developments (Stanley et al., 2018 and Mosier et al., 2021) show positive soil C balance from using rotational grazing and could help beef production become a C sink. The same ecosystem approach could be applied to confinement conditions, and this would require accounting for both C inputs from feed and C outputs, including CO_2 and fecal C. Carbon is recycled back to crop production in the form of manure which benefits feed production. Evidence suggests that manure application improves soil C (Buyanovsky and Wagner 1998) even after losses in C (28.0%, 2.5% as CH_4 and 97.5% as CO_2) and N (6.1%, 13% as N_2O and 87% as NH_4-N%) during 165 days of manure stockpiling (Bai et al. 2020).

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Table A1. Ingredient composition of confinement diet fed to alternative cow-calf system by year during pen-scale GHG measurement[1]

	Gestation			Lactation		
Nutrient Composition, % DM	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
DM, %	66.9	66.9	55.1	66.7	67.3	63.8
OM, %[1]	90.8	90.8	92.1	90.8	90.8	92.4
GE, Mcal per kg	4.4	4.4	4.3	4.4	4.4	4.3
TDN, % of DM	63.7	64.8	69.6	63.7	64.8	66.8
Fat, % of OM	6.3	6.2	5.3	6.3	6.2	4.3
Protein % of OM	18.3	18.1	14.7	18.3	18.1	14.4
Carbohydrate, % of OM	66.4	67.8	72.1	66.4	67.8	73.8
Ash, % of DM	9.2	9.2	7.9	9.2	9.2	7.6
Carbon, % of OM[2]	42.8	43.3	42.2	42.8	43.3	41.9

[1] Modified distillers grains plus solubles.

[2] Measured in lab analysis

[3] Using standard values from NASEM (2016)

Table A2. Nutrient profile and estimated methane production from grazed forages in both CONV and ALT systems.

	Bromegrass	Oat Forage	Corn residue
Ash, % of DM[1]	8.84	9.73	11.10
Carbon, % of OM[1]	41.60	38.63	40.69
Organic Matter[1]	91.16	90.27	88.90
Neutral detergent fiber[1]	65.92	52.71	70.83
GE, Mcal/kg[1]	3.99	4.19	3.86
GE loss, %[3]			
Median			
Low	5.28	3.43	5.47
Med	6.69	6.50	6.92
High	6.42	5.97	6.49
Min	5.36	3.00	5.44
Max	10.48	8.06	12.06
Average	6.99	4.19	7.33
Median	6.42	3.56	6.49
Methane, g/d[3]			
Min	182.3	106.9	16.3
Max	356.5	282.2	313.3
Average	237.6	154.5	197
CH4, g/kg DM[3]			
Min	16.07	9.43	17.38
Max	31.44	24.89	34.53
Average	20.96	13.62	21.72

[1] Using standard book values from NASEM (2016)

[2] Empirical calculation from NASEM 2016

Table A3. Carbon intake, loss and global warming potential from cows in CONV and ALT systems during both lactation and gestation under grazing and feedlot confinement conditions.

	Gestating diet	Lactating diet	Brome pasture	Oat Forage	Corn residue	Grass hay
Diet TDN, % [1]	66.0	65.1	61.7	63.0	49.8	48.28
Diet OM, % [2]	91.2	91.2	91.2	90.3	88.9	91.2
Carbon in						
OM intake by cow[1], g	6317	8336	12805	20951	7945	10301
C intake[2], g						
Cow, feed C[3], g	2700	3553	5327	8793	3233	4285
Calf, milk and feed C[4], g		355	1143	1052		
Carbon out						
C loss from calf CH_4[5], g	0	7	39	41	0	0
C loss from calf CO_2[6], g	0	363	747	776	0	0
C loss from cow CH_4[7], g	103	124	223	232	144	0
C loss from cow CO_2[7], g	1621	1553	4500	4264	2018	2057
C loss from cow feces and urine[8], g	918	1241	2040	3253	1623	2216
C loss from calf feces and urine[8], g	0	18	201	276	0	
C loss from milk[9], g	0	355	710	355	0	0
C retained in calf or conceptus[10], g	12	135	140	157	12	12
C retained in cow[11], g	0	0	0	0	0	0
C balance[12], g	47	114	-2131	492	-564	0
C loss from calf CH_4, % of cow intake	0.0	0.2	0.6	0.4	0.0	0.0
C loss from calf CO_2, % of cow intake	0.0	9.3	11.6	7.9	0.0	0.0
C loss from CH_4, % of intake	3.8	3.2	3.4	2.4	4.4	0.0
C loss from CO_2, % intake	60.0	39.7	69.5	43.3	62.4	63.6
C loss from cow feces and urine, % of intake	34.0	31.7	31.5	33.0	50.2	68.6

C loss from calf feces and urine, % of intake	0.0	0.5	3.1	2.8	0.0	0.0
C loss from milk, % of intake	0.0	9.1	11.0	3.6	0.0	0.0
C retained in calf or conceptus. % of intake	0.4	3.5	2.2	1.6	0.4	0.4
C retained in cow, % of intake	0.0	0.0	0.0	0.0	0.0	0.0
C balance, %	1.7	2.9	-32.9	5.0	-17.4	0.0

[1] Gestating and lactating diet TDN determined from weighted average ingredient TDN values from NASEM 2016. Bromegrass and Oat forage from NASEM 2016. Corn residue values were adapted from Burken (2014), Gutierrez-Ornelas and Klopfenstein (1991), and Lamm and Ward (1981) and

[2] Organic matter (OM). Diet OM values for gestating and lactating diets determined from 1-ash content of sampled ingredients. Brome pasture, oat forage, and corn residue values from NASEM (2016)

[3] Dry matter intake (DMI) measured for gestation and lactation diets fed in confinement pens. DMI modeled for brome pasture, oat forage and corn residue based on methane loss and NASEM 2016 values for gross energy loss. OMI equal to DMI x OM%

[4] Calf carbon intake calculated from milk intake (7.1 kg per calf per day for lactation and oat forage and 14.2 kg for brome pasture) which is based on calf BW (Mulliniks et al. 2020) and feed intake (1.04 kg per calf per day for lactation and oat forage and 1.66 kg DM for brome pasture) based on milk intake (Abdelsamei et al., 2005).

[5] Methane loss from calf estimated from the following equation based on BW: $CH_4 = 0.0013(BW)^2-0.2787(BW)-17.738$

[6] Carbon dioxide loss from calf estimated from the following equation based on BW $CO_2 = 0.0309(BW)^2 + 12.387(BW) + 260.77$

[7] Cow CH4 and CO2 loss measured in pen chamber during gestation and lactation diet feeding and using eddy covariance (EC) when grazing brome pasture, oat forage, and corn residue.

[8] Cow urine and feces loss equal to 1 - TDN and assuming indigestible portion C content equal to C content of feed. Calf milk C loss calculated from milk TDN = 95% (Diaz et al. 2000) and TDN of feed intake equal to cow diet TDN, which determined C loss by difference.

[9] Carbon loss due to milk production equal to calf C intake of milk carbon (7.1 kg milk for gestation and lactation and 14.2 kg milk for brome pasture) and milk C content calculated assuming milk composition equal to 3.5% fat (70% C), 3.2% protein (43% C), and 4% sugar (40% C) or 5% C

[10] Carbon retention in conceptus calculated from average conceptus growth (39 to 40 kg birthweight) divided by 280 days and average calf gain (0.88 for lactating or oat forage and 1.19 kg per day for brome pasture). Estimate carbon content of fetus (EBWconceptus = Birth weight (kg)*(0.891) and weaned calf EBWweaning = Weaning weight*(0.891) and based on body composition

body Protein, kg = 0.235(EBW) – 0.00013(EBW)3 – 2.418 Body Fat, kg= 0.037(EBW) + 0.00054(EBW)2 -0.610 and protein 43% C and fat 70% C.

[11] Cow retention assumed to be zero based on body condition score. BCS was different based on treatment (ALT or CONV) but remained unchanged from year to year within treatment.

[12] Carbon balance calculated by subtracting all carbon output (CH_4, CO_2, feces, urine, milk, retention) from intake

Table A4. Water intake for cows and calves raised in CONV pasture based or ALT confinement-based herds[1,2]

CONV

						Temperature		
Gestation	Total L	Days	Free water intake	Water from feed	Total water intake	Low °C	High °C	Precipitation, cm
Corn residue grazing[3]								
	5107	140	34.2	2.2	36.5	-4.5	7.1	14.5
Grass hay[4,7]								
	1229	48	23.6	2.0	25.6	3.85	15.9	3.07
Lactation								
Grass Pasture[5]								
	22790	177	72.6	56.2	128.8	17.1	29.3	46.4
Growing[5,6]								
	4999	116	39.4	3.7	43.1	-4.2	7.2	14.7
Finishing[5]								
	6750	162	34.6	7.0	41.7	7.6	20.0	25.7
	40875	643	63.57					
HCW per cow exposed, kg			321					
L per kg HCW per cow exposed			127.3					

[1] Treatment = conventional cow-calf system (CONV) utilizing summer pasture, corn residue, and calving in an alternative cow-calf system (ALT) calving in July/August and utilizing drylot, fall forage oat grazing, and corn residue grazing

[2] Gestation and lactation data reported as L per pair. Growing and finishing data reported per calf. Includes free water but not water in feed

[3] Measured using water flow meter in confinement (Neptune T10, Neptune Technology Group) or pasture (Model M, ARAD Water Measuring Technologies)

[4] Measured using water flow meter (Manifold Flow Meter 3 inch, Banjo Liquid Handling Products, Crawfordsville, IN) as water was delivered with truck

[5] Measured during growing and finishing phases. Each water meter measured 2 replicates of calves (4 replicates per treatment)

[6] To prevent ice buildup, water overflows flowed continuously from December 12th, 2020 to February 26, 2021. This averaged 36.9 L per calf per day during the growing period. That data has been subtracted from water intake data above.

[7] Data during the calving period of March 15 to May 1st when CONV cows were fed grass hay no water measurements were taken. 35.5 L per day was estimated from Wagner and Engle (2021)

[8] Weather data reported from the National Weather Service www.weather.gov daily mean data for Wahoo, NE

Table A5. Water intake for cows and calves raised in CONV pasture based or ALT confinement-based herds[1,2]

				ALT				
						Temperature		
Gestation	Total L	Days	Free water intake	Water from feed	Total water intake	Low °C	High °C	Precipitation, cm
Corn residue grazing[3]								
	2152	59	34.2	2.2	36.5	-5.1	6.2	5.6
Limit feed - confinement[5]								
	6231	124	46.2	4.1	50.3	11.2	23.4	24.7
Lactation								
Limit feed - confinement[5]								
	6409	98	60.7	4.7	65.4	15.3	27.9	27.1
Secondary Annual Forage Grazing[2]								
	14007	84	50.7	116.0	166.7	-4.6	7.4	9
Growing[5,6]								
	3529	116	26.7	3.7	30.4	0.9	12.6	14.7
Finishing[5]								
	11575	228.0	43.7	7.0	50.8	7.5	20.0	50.8
	43903	709	61.92					
HCW per cow exposed, kg			333					
L per kg HCW per cow exposed			131.8					

[1] Treatment = conventional cow-calf system (CONV) utilizing summer pasture, corn residue, and calving in an alternative cow-calf system (ALT) calving in July/August and utilizing drylot, fall forage oat grazing, and corn residue grazing

[2] Gestation and lactation data reported as L per pair. Growing and finishing data reported per calf. Includes free water but not water in feed

[3] Measured using water flow meter in confinement (Neptune T10, Neptune Technology Group) or pasture (Model M, ARAD Water Measuring Technologies)

[4] Measured using water flow meter (Manifold Flow Meter 3 inch, Banjo Liquid Handling Products, Crawfordsville, IN) as water was delivered with truck

[5] Measured during growing and finishing phases. Each water meter measured 2 replicates of calves (4 replicates per treatment)

[6] To prevent ice buildup, water overflows flowed continuously from December 12th, 2020 to February 26, 2021. This averaged 36.9 L per calf per day during the growing period. That data has been subtracted from water intake data above.

[7] Data during the calving period of March 15 to May 1st when CONV cows were fed grass hay no water measurements were taken. 35.5 L per day was estimated from Wagner and Engle (2021)

[8] Weather data reported from the National Weather Service www.weather.gov daily mean data for Wahoo, NE