THESIS

EFFECTS OF ORIGIN ON ENTERIC GREENHOUSE GAS EMISSIONS AND GROWTH PERFORMANCE

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ABSTRACT

EFFECTS OF ORIGIN ON ENTERIC GREENHOUSE GAS EMISSIONS AND GROWTH PERFORMANCE

Methane (CH_4) emissions from cattle across various origins remain inadequately understood, representing a significant knowledge gap for sustainable beef production. This study investigates enteric CH_4 emissions from yearling steers of different origins and under different management practices. The experiment was divided into two phases. In Phase 1, steers were managed according to local practices: grazing in Colorado and confined background feeding in Nebraska and Wyoming. In Phase 2, all steers were moved to a common grazing environment in Colorado. Methane emissions were measured using the Automated Head Chamber System (AHCS).

During Phase 1, CH_4 emissions and growth performance varied significantly among the groups, influenced by diet and management. Nebraska steers had the greatest CH_4 production (MP), while Colorado steers had the least, reflecting differences in diet composition and feed intake. However, CH_4 intensity (MI) was similar across all groups due to compensatory differences in average daily gain (ADG). In Phase 2, when all steers grazed under the same conditions, Colorado steers exhibited the greatest ADG and MP, indicating better adaptation and suitability to the grazing system than Nebraska and Wyoming steers.

Results suggest that enteric CH_4 emissions are influenced by cattle's origin and previous management. This highlights the need for context-specific studies to accurately assess the

sustainability and greenhouse gas (GHG) mitigation strategies for grazing beef cattle. Further research should address these variations to improve the accuracy of CH_4 emissions estimates in different rangeland ecosystems.

This study also evaluated different CH_4 prediction equations using various statistical approaches (RMSE, R^2, Mean and Slope bias, correlation coefficients, and least square differences). Three equations showed potential for predicting CH_4 emissions for the steers of the current study: the one by Ellis et al. (2009), the one by Escobar-Bahamondes et al. (2016), and Moraes et al. (2014). Even though the CH_4 estimated by these equations was similar to the observed, there is room for improvement in the development of accurate equations to predict cattle enteric CH_4 emissions in grazing systems.

Lastly, the animals were ranked in both Phases by their MI and MP, and it was evaluated if the animals changed their ranking in Phase 1 when moved to Phase 2. Animals from all origins experienced shifts in their classification categories, indicating the dynamic nature of CH_4 across different contexts. However, it was observed that steers from the Wyoming group exhibited the most significant changes in MP classification categories when transitioning from a confinement system with grain-based diets to a grazing system. Based on the current results, the background of the steers may need to be considered when evaluating sustainability goals in beef cattle production systems.

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DEDICATION

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CHAPTER 1: LITERATURE REVIEW

INTRODUCTION

Global warming is a pressing environmental issue driven by the accumulation of greenhouse gases (GHGs) in the Earth's atmosphere (Watson et al., 1995; Denning, 2022). Methane (CH_4), a potent GHG, originates from different sectors, including agriculture and beef cattle production (The Environmental Protection Agency, 2023). Understanding the CH_4 production across different beef production systems, such as grazing and feedlots, is crucial for developing effective mitigation strategies system-wide.

In the United States (US), with its significant cattle population, various farming practices are employed, ranging from extensive pasture-based systems to intensive feedlot operations. Cattle often transition from grazing systems into confinement, usually in different states, to complete their cycle (Drouillard, 2018). However, the effects of transitioning cattle between these systems on CH_4 emissions and livestock performance remain poorly understood.

This thesis aims to address this knowledge gap by investigating the impact of management practices on CH_4 emissions and cattle performance. By studying these factors across different phases of cattle production on cattle originated from different locations and experiencing different management practices, the goal is to discover insights to inform the development of sustainable beef production methods.

GLOBAL WARMING AND THE ROLE OF GREENHOUSE GASES

Global warming arises as a result of changes in the Earth's energy budget, resulting from an imbalance in the equilibrium between the solar energy and the energy radiated back into space, keeping the excess energy trapped in the atmosphere, causing global temperature to increase (Watson et al., 1995; Denning, 2022). When radiation attempts to pass through the atmosphere, 94% of the energy is trapped by the atmosphere, while only 6% passes through it; therefore, the heat remains in the atmosphere (Watson et al., 1995; Denning, 2022).

In this context, heat accumulation in the atmosphere directly results from atmosphere gas composition. Ninety-nine percent of Earth's atmosphere is primarily composed of two major molecules: 78% nitrogen gas (N_2) and 21% oxygen gas (O_2; National Oceanic and Atmospheric Administration - NOAA, 2023). Nitrogen gas and O_2 consist of only two atoms each and have a relatively limited capacity to trap energy. Therefore, N_2 and O_2 contribution to global warming is minimal (Denning, 2022). However, the atmosphere also contains water vapor (H_2O, 4% of the total volume) and small amounts of other gases that consist of three or more atoms, such as CH_4 (0.00017%), carbon dioxide (CO_2; 0.035%), and nitrous oxide (N_2O; 0.000031%; NOAA, 2023). Those gases are key GHGs notable for their ability to trap thermal energy due to their molecular structures (Herzog, 2009). When evaluating a period of 100 years, CH_4 stands out as a potent GHG, having 25 times greater global warming potential (GWP) compared to CO_2, with an atmospheric lifespan of 12 years. Moreover, N_2O has a 273 greater GWP than CO_2, with an atmospheric lifespan of 109 years (Intergovernmental Panel on Climate Change, 2023).

Previous research has reported that an increased concentration of GHGs, such as CH_4, CO_2, and N_2O, in the atmosphere leads to a greater potential for retaining heat in the atmosphere and, therefore, increasing global warming (Schiffer and Unninayar, 1991; Denning, 2022). The increase in GHG emissions, especially CO_2, CH_4, and N_2O, has become critical, increasing worldwide by

3.87% from 2020 to 2021 and 0.75% from 2020 to 2021 (CO_2, CH_4, and N_2O), US accounting for 11% of the global GHG emissions (Jones et al., 2024). Moreover, Herzog (2009) reported that global GHG emissions comprise 77% CO_2, 15% CH_4, and 7% N_2O, and the four primary sources of these gas emissions are electricity and heat (24.9%), transportation (14.3%), industry (14.7%), and agriculture (13.8%), respectively.

THE IMPACT OF AGRICULTURAL AND BEEF CATTLE PRODUCTION ON GHG EMISSIONS

In the US, the agriculture sector is responsible for 35% of the CH_4 emitted annually and 10% of the country's total GHG emissions (beef and dairy represent 4.4% of the total GHG; The Environmental Protection Agency, 2023). Worldwide, it is estimated that dairy and beef cattle production (livestock and manure) expressly represent only 5.4% of the world's total GHG emissions, mainly CH_4 (Herzog, 2009). Enteric CH_4 is generated in the rumen of livestock as a hydrogen sink, produced by microbes fermenting feed in the rumen; the amount of enteric CH_4 produced by a ruminant animal is directly correlated with the end products of ruminal carbohydrate fermentation (Fahey and Berger, 1993). According to McDonald and Warner (1975), CH_4 in the rumen is generated through microbial metabolism, primarily via the Embden-Meyerhof pathway, leading to acetate production. This process releases energy through substrate phosphorylation, forming acetyl-CoA and adenosine triphosphate (ATP). Therefore, CH_4 is produced from formate, serving as an electron sink for ATP production (McDonald and Warner, 1975). Enteric CH_4 production (MP) is greatly influenced by cattle dietary factors (i.e., forage-based diet vs. grain-based diets), particularly the acetate-to-propionate ratio, with greater acetate levels (forage-based diets) increasing CH_4 output (Van Soest, 1982).

The United States beef cattle production system

On January 1st, 2023, the total US cattle population was 88.8 million head: 28.9 million beef cows, 18.8 million heifers (dairy and beef), 16.1 million steers, 13.7 million were calves and 11.3 million other cattle such as bulls and dairy cows (USDA Economic Research Service, 2023).

Cow-calf operations are characterized by raising calves on pasture with minimal inclusion of supplemented grain in cattle diets (USDA Economic Research Service, 2023). The US beef cow location is dispersed, 95% of the animals are in 31 States. The central region has 55% of the national herd, with a diet based on native grasslands supplemented with crop residues, protein concentrates, and harvested forages. The Western region has 20% of the national herd, and the diet in this region is based on grazing on federally owned land (leased to producers) as well as private land. The Southeastern region has 20% of the national herd, this region is characterized by heavily improved pastures and smaller production systems (Drouillard, 2018). Typically, most calves are weaned between the ages of 6 and 9 months, weighing approximately 180 to 320 kg (Macdonald and Mcbride, 2009). Calves often follow one of two different paths: 40% go to a feedlot, and 60% go to backgrounding/stocker systems (to gain more weight) before going to a feedlot (Drouillard, 2018).

In contrast, cattle-feeding operations, mainly focusing on the finishing phase, dominate the market for grain-fed-finished cattle with larger facilities. The cattle raised in grazing systems usually are transported to this type of system which is concentrated in a few regions of the country (USDA Economic Research Service, 2023), mainly in Nebraska (20%), Texas (19%), Kansas (17%), Iowa (9%), Colorado (7%), California (3%), Minnesota (3%) and South Dakota (3%) (USDA NASS, 2022 Census of Agriculture). Moreover, according to Harper et al. (1999), enteric

GHG emitted by farm animals, especially ruminant livestock, differs significantly between individual production systems (i.e., grazing vs. feedlot systems).

Grazing systems

The grazing system is a system in which livestock is managed on intensive or extensive forage-based systems. In the US, nearly 36% of the land is used for grazing ruminants such as cattle and sheep (Bigelow and Borchers, 2017). According to Rotz et al. (2009), a well-managed grazing system can reduce the carbon footprint of livestock production and mitigate environmental impacts associated with animal protein production, including reducing enteric GHG emissions. In this context, reducing MP, the primary enteric GHG emitted by ruminant animals (Herzog, 2009), is crucial to reducing the overall environmental impact of a grazing system. Consequently, efforts have been directed toward quantifying MP from cattle and developing strategies to mitigate and reduce these emissions within grazing systems.

Several factors can influence the enteric MP of grazing livestock. In a study with cows and heifers grazing warm-season pastures of bahiagrass or bermudagrass, overseeded with annual ryegrass forages during summer and winter, DeRamus et al. (2003), observed that enteric MP ranged from 89 to 249 g/head/day. These authors explained that the variation in enteric MP may be because heifers had not reached their mature size (lighter body weights) and emitted less enteric MP (120 to 240 and 86 to 166 enteric CH_4 (g/day) for cows and heifers, respectively); moreover, forage quality changed throughout the year, where better forage quality led to less enteric MP (DeRamus et al., 2003). Results from DeRamus et al. (2003) are consistent with the results reported by Pavao-Zuckerman et al. (1999), who observed that enteric MP from grazing steers were different across three different seasons of the year (spring, summer, and winter) ranging from 166 to 190 g/day, 148 to 190 g/day, and 110 to 120 g/day, respectively (Pavao-Zuckerman et al.,1999). Lassey et al. (1997) reported enteric MP rates from 229 to 313 g/day from dairy cows grazing *Lolium perenne* and *Trifolium repens ad libitum*. These authors explained that dairy cow dry matter intake (DMI) accounted for 50% of the enteric MP variance, where greater DMI led to greater MP (Lassey et al., 1997).

Results of the previously mentioned studies indicate that daily enteric MP in grazing systems is variable. The major factors that influence enteric MP in grazing systems are differences in cattle body weights (greater body weight, greater MP), cattle DMI (greater DMI, greater MP), season of the year, and cattle diet (pasture) quality measured as %CP and %ADF (better quality, less MP).

Confinement systems

In the US, 18% of the cattle herd are housed in confined systems (National Agricultural Statistics Service, 2023). A confined system, also known as a feedlot, is where cattle are fed a specialized diet, usually to promote rapid weight gain and efficiency. In confinement systems, cattle are housed in pens, where their diet, water, and health are carefully monitored (Endres and Schwartzkopf-Genswein, 2017). As described by Drouillard (2018), feedlot diet fed to cattle has a net energy for gain ranging from 1.50 to 1.54 Mcal/kg, with its main ingredients being grain (i.e., corn) and grain byproducts (i.e., dry distillers grains plus solubles).

Similar to grazing systems, enteric MP from livestock in confinement can also vary depending on various factors. Beauchemin and Mcginn (2005) reported that during the backgrounding phase, heifers receiving a barley-silage-based diet emitted an average of 171 g of enteric CH_4/day (DMI = 6.96 kg/day) compared to an average of 130 g of enteric CH_4/day for heifers receiving a corn-silage-based diet (DMI = 5.34 kg/day). During the finishing phase, the same heifers were fed a corn-based diet and emitted on average 62 g of enteric CH_4/day (DMI = 6.83 kg/day), while those on a barley-based diet emitted 80 g/day (DMI = 6.17 kilograms per day). These authors concluded that enteric MP was primarily influenced by cattle DMI rather than diet (Beauchemin and Mcginn, 2005). Moreover, enteric MP was also affected by the quality of the diet, the type of grain fed (corn vs. barley), and cattle ruminal pH (Beauchemin and Mcginn, 2005).

McGinn et al. (2008) observed that enteric MP of animals fed in a feedlot in Australia (cattle body weight ranged from 265 and 620 kg) was 166 enteric CH_4 (g/d) when cattle were receiving a basal diet of reconstituted sorghum grain (75%), forage (18%), and grain and supplements (7%, with 2 to 3% being vegetable of oil), while enteric MP of animals fed in a feedlot in Canada (cattle body weight between 350 to 600 kg) was 214 (g/day) when cattle were receiving a basal diet of 90% barley grain plus barley silage, corn silage, and supplements. The authors explained that this variation in enteric MP was due to several factors, such as cattle weight (greater weight led to greater MP), DMI (greater DMI led to greater MP), and fat concentration in the diet (greater fat concentration led to lesser MP); moreover, a decline in enteric MP was observed in Australia during the day time compared to the night time due to reduction in cattle DMI while animals were going through heat stress conditions (McGinn et al., 2008).

Enteric MP in confinement systems is variable, ranging from 62 to 214 g/head/day. These variations result from differences in factors such as feed intake, diet quality and composition, cattle body weight, and environmental conditions. Additionally, differences in gas measurement techniques could contribute to the observed variability (Johnson and Johnson, 1995).

METHODS TO MEASURE THE VARIABLES OF INTEREST IN MP EXPERIMENTS

Researchers must consider specific variables such as DMI and enteric MP to effectively measure enteric MP in an experiment setting. This involves selecting appropriate methods for measuring enteric GHG emissions and assessing DMI. Dry matter intake plays a crucial role in determining enteric MP, as it is essential for estimating CH_4 yield and serves as a key factor influencing enteric MP (Lassey et al., 1997; Beauchemin and Mcginn, 2005; McGinn et al., 2008).

Measuring DMI

Direct and indirect are two primary methods for measuring DMI in beef cattle production systems. The direct method involves physically measuring the actual feed intake by the animals. This can be conducted using devices like SmartFeed (C-lock Inc., 2023). Whereas indirect measurements estimate DMI based on various parameters or factors associated with the animals, such as digesta markers (Minson and McDonald, 1987; Guinguina et al., 2019) or crude protein (CP) and acid detergent fiber (ADF) present in the cattle diet (National Research Council, 1996). The methodological approach utilized by a cattle producer or researcher will depend on the system (grazing or confinement), technologies available, time, budget, and the type of system (grazing vs confinement).

Grazing systems

Estimating cattle DMI in grazing systems can be more complex than in a confinement system due to many variables that impact the cattle DMI (Coleman, 2005). These variables include selective grazing, herbage mass, sward structure and composition, weather and environmental factors, and the complexity of the grazing process itself (Coleman, 2005; Galyean and Gunter, 2016). Although there is no scientific consensus on how to measure DMI in grazing systems, some of the established methods are indirect measurements of pasture (DMI of forage is estimated according to the pasture disappearance over time), external markers (used to determine the fecal output) and internal markers (used to determine the digestibility of the diet); knowing the fecal output and the digestibility of the diet the cattle DMI can be determined. Mathematical approaches or models and sensor-based estimation are also mechanisms to measure DMI (Velásquez et al., 2018; Smith et al., 2021). Among these approaches, this review will focus on internal and external markers and mathematical approaches.

External markers

Animals are dosed with a known amount of an external marker; fecal samples are collected and analyzed to determine the concentration of the external marker, and fecal output (total amount of feces defecated by the animal) is determined (Velásquez et al., 2018). External markers should not influence digestion, be non-absorbable, have characteristics similar to dietary components, and maintain sufficient concentration in fecal samples (Fahey and Jung, 1983). Moreover, external markers, such as chromic oxide, n-alkanes, and titanium dioxide, are administered to animals to estimate digest flows (Smith et al., 2021).

According to Glindemann et al. (2009), titanium dioxide (TiO_2) is an external marker used to estimate cattle feed intake. The method involves administering TiO_2 to animals over several days, typically at least five days (Meyers et al., 2006). Studies have varied in dosage and duration of TiO_2 administration. Meyers et al. (2006) administered five g daily to sheep for seven days, while Titgemeyer et al. (2001) used 10 g daily for 14 days in cattle, collecting samples during the last seven days. According to Glindemann et al. (2009), fecal recovery rates stabilized after five days of TiO_2 dosing in grazing sheep. Similar to the TiO_2, other external markers are also used to estimate the fecal output. Chromic oxide dosages vary from five g/day in sheep to 16 g/day in cattle (Smith et al., 2021). This external marker will stabilize after five days in cattle (Rosiere et al., 1980)

Internal Markers

Internal markers are naturally occurring substances in feed resources used to estimate digestibility. Using the fecal output determined with the external markers and the digestibility determined with internal markers, cattle intake can be determined by dividing fecal output by one minus the digestibility (Velásquez et al., 2018). Some examples of internal markers are biogenic silica, lignin, and indigestible neutral detergent fiber (iNDF) (Smith et al., 2021). Most of these elements are related to the cell wall and its elements (Smith et al., 2021).

Indigested Neutral Detergent Fiber (NDF) serves as a common internal marker for calculating the digestibility of ruminant diets (Battelli et al., 2020). The ruminant animal does not digest this fraction of the feed, and therefore, it meets the requirements for acting as a marker (Smith et al., 2021).

Mathematical equations

Different authors have explored DMI prediction in beef and dairy cattle systems, developing different DMI prediction models (Minson and McDonald, 1987; National Research Council, 1996). These models differ in their complexity and the variables they incorporate to estimate the DMI of ruminants.

Minson and McDonald (1987) created a DMI prediction equation that used the shrunk body weight (SBW) and the ADG rate of the animal.

Equation 1 (Minson and McDonald, 1987):

$$\text{DMI kg DM/d} = (1.185 + 0.00454\ \text{BW} - 0.0000026\ \text{BW}^2 + 0.315\ \text{ADG})^2$$

Meanwhile, the Nutrient Requirements of Beef Cattle Equation for all-forage diets (NRC, 1996, Eq:- CP__ADF) contemplates characteristics of the diet as well as the live weight to determine the DMI.

Equation 2 (NRC, 1996):

$$\text{DMI kg/kg BW}^{0.75} = 0.002774 \times \text{CP percent in the forage} - 0.000864 \times \text{ADF percent in the forage} + 0.09826$$

McMeniman et al. (2010) also developed an equation for estimating the DMI of feedlot cattle using the shrunk initial body weight (ISBW; equation 3).

Equation 3 (McMeniman et al., 2010):

$$\text{DMI, kg/d} = 3.830 + 0.0143 \times \text{IBW}$$

Furthermore, another equation presented by the NRC (2016) estimates DMI by multiplying the BW by 0.0225 (equation 4).

Equation 4 (NRC, 2016):

$$\text{DMI, kg/d} = \text{BW} \times 0.0225$$

Additionally, the IPCC (2006) developed an equation (Equation 5) for estimating the DMI using the BW and the net energy of maintenance (NEm). The NEm can be found in Table 10.8 of the IPCC (2006) report.

Equation 5 (IPCC, 2006)

$$\text{DMI} = \text{BW}^{0.75}[(0.2444 \times \text{NEm} - 0.0111 \times \text{NEm}^2 - 0.472)/\text{NEm}]$$

Where DMI = estimated DMI (kg/d), BW = Cattle SBW (kg), IBW = Cattle IBW (kg), ADG = Cattle ADG (kg/d), CP = Estimated CP (%) in the forage, ADF = Estimated ADF (%) in the forage, NEm = estimated dietary net energy concentration of diet (MJ/kg).

Confinement systems

Indirect measuring of cattle DMI, such as markers, can also be used in confinement systems, as well as direct techniques to measure the DMI, such as individual feed intake systems. The individual feed intake system, such as the SmartFeed system, tracks the feed consumption of each animal by tracking the kilograms of feed taken from the feed bunk. This system operates as follows: it has a feed bunk equipped with a scale and allows one animal to access the feeding unit at a time. When an animal approaches the system, the radio frequency identification (RFID) reader identifies the unique ear tag associated with that specific animal. The calculation of DMI in this system is based on the variance in the initial and final weight of feed within the bin while the animal has its head in the bin (Reuter et al., 2017; Durst et al., 2022; C-lock Inc., 2023).

Measuring GHG

Various methods exist for estimating enteric MP, such as respiration chamber, Sulfur hexafluoride (SF_6), and GreenFeed systems (Garnsworthy et al., 2019).

Respiration chamber

Garnsworthy et al. (2019) stated that a respiration chamber measures enteric MP and other gases. An individual animal (or occasionally more) is confined within the chamber for a duration ranging from two to 7 days. The gas concentration is estimated at the chamber's air inlet and outlet vents. The difference between outlet and inlet concentrations is multiplied by the airflow (accounting for the standard temperature and pressure) to determine the enteric MP rate.

According to Hristov et al. (2018), this system is considered the gold standard for enteric MP measurement when appropriately operated and calibrated accurately. It has the advantage that it can provide accurate measurements of enteric MP if all variables are controlled effectively. However, it has some disadvantages, such as measurement variability that can arise from airflow rate, air mixing dynamics, and daily feed intake stability (the animals confined in the chamber may get stressed and decrease their DMI). Intermittent door opening for activities such as milking events in dairy cows and cleaning events in the chamber can introduce gaps in data collection, potentially leading to an overestimation of enteric MP (Hristov et al., 2018).

Sulfur hexafluoride

Johnson et al. (1994) explained that the SF_6 technique, developed by Zimmerman, for measuring enteric MP in cattle involves introducing a precisely known quantity of SF_6 into the reticulum-rumen over a designated period, typically 22 hours. Subsequently, collecting the gases emitted by the animal (CH_4 and SF_6), the collected gases from this period are analyzed to determine the concentrations of both CH_4 and SF_6. The calculation involves determining the CH_4/SF_6 ratio of concentrations, adjusted for background concentrations.

The SF_6 technique offers the advantage of having the animal in its environment and can produce accurate results when executed properly. However, variability in MP measurements has been noted, potentially due to factors such as SF_6 release rate, duration of measurements, and background air concentrations. Proper ventilation and background air correction are required to reduce variability (Hristov et al., 2018).

GreenFeed

The GreenFeed system (C-Lock Inc., Rapid City, SD), developed by Zimmerman, as described by Hristov et al. (2018), offers real-time measurements and is simple to operate.

Accurate estimates of enteric MP can be obtained by controlling animal visits to accommodate diurnal patterns. However, the frequency and timing of animal visits and outdoor conditions such as wind speed or temperature can influence measurement accuracy. This underscores the importance of meticulously controlling experimental conditions to ensure data reliability.

Hristov et al. (2015) highlighted the benefits of the GreenFeed method compared to other systems, such as environmental chambers. With GreenFeed, cattle can freely move within their natural surroundings without confinement. The animals use the machine voluntarily and independently.

However, GreenFeed exclusively captures emissions originating from the anterior section of the animal (87% of the enteric CH_4; Murray et al., 1976) and does not assess GHG (13%) generated in the large intestine (Hammond et al., 2016). Moreover, the animal must be acclimated to the machine, and the acclimatization period varies between animals and systems (Garnett, 2012; Hristov et al., 2015). Furthermore, the accuracy of the animal's emissions measurement is contingent upon the animal's head being fully inserted into the GreenFeed (Hristov et al., 2015).

THE IMPACT OF BEEF PRODUCTION SYSTEMS ON THE ENVIRONMENT

Considering the broader ecological context, it is essential to recognize the ecosystem services provided by grasslands when evaluating the impact of beef cattle production in grazing systems. These services encompass various aspects, including maintaining high biodiversity (Habel et al., 2013; Erb et al., 2016), erosion control, participation in the carbon cycle, and the water and nitrogen cycle (Erb et al., 2016; Bengtsson et al., 2019).

Ecosystem services

The ecosystem services provided by grasslands should be considered when evaluating the impact of beef cattle production in grazing systems. There are different ecosystem services that grasslands offer, the most noticeable one being the provision of feed for livestock, but there are many others, such as maintaining a high biodiversity (Habel et al., 2013; Erb et al., 2016), erosion control, playing a role in the carbon cycle, as well as in the water and nitrogen cycle (Erb et al., 2016; Bengtsson et al., 2019)

VARIABLES THAT INFLUENCE CATTLE EMISSIONS

When estimating the impact on the GHG emissions or "carbon footprint" for a product or activity, it is considered how much GHG is emitted, absorbed, or stored when the product is produced and used (Peters, 2010). Knowing the carbon footprint of any agricultural product is crucial to understanding the impact of that product on the environment. Al-Mansour and Jejcic (2017) developed the following equation to calculate the carbon footprint of an agricultural product (CFAP):

CFAP (kg CO_2eq/Ton) = Total GHG emissions/ Agricultural product yield on one hectare(ton/ha)

Based on this equation, two ways exist to modify the GHG emissions per product unit. The first is to increase the efficiency of production or the total amount of an agricultural product (denominator), and the second is to reduce the number of gases produced (nominator), which can be achieved by fixing more carbon into the system or emitting less.

Previous research has reported that there are different ways to decrease enteric GHG emissions, such as forage type fed to cattle (Archimède et al., 2011), adding tannins in cattle diets

(Woodward et al., 2001; Tiemann et al., 2008) or feeding monensin or unsaturated fats to cattle diet (Beauchemin and McGinn, 2006). Moreover, there are also different ways to increase production efficiency, such as modifying diet quality and digestibility (Harper et al., 1999a; Beauchemin and Mcginn, 2005), genetic selection (Basarab et al., 2013; Chagunda et al., 2009), and improving cattle and diet management (Hart et al., 2009).

Improve production efficiency and reduce enteric MP

It is possible to decrease the carbon footprint by improving production efficiency using different tools (nutrition, management, genetics). If the unit production per individual animal increases, the number of animals needed to produce the same amount of food products decreases, and the production system emits less enteric CH_4 (Boadi et al., 2004; Basarab et al., 2013).

Different management practices can improve animal husbandry efficiency, such as modifying diet quality and digestibility (Hart et al., 2009) and improving or selecting animals by selective characteristics (Beauchemin and Mcginn, 2005) such as residual feed intake (Basarab et al., 2013).

Diet quality and digestibility

Adjustments in management may not only increase the ADG of the animals by enhancing forage quality but also reduce the total grazing period, consequently lowering enteric MP per unit of animal product (Montossi et al., 1995; Beauchemin et al., 2008).

Hart et al. (2009) reported a decrease in enteric CH_4 emissions per kilogram of product by improving pasture management. These authors explained that providing cattle with less mature forage rich in carbohydrates enhances digestibility (Hart et al., 2009). Additionally, Soto-Navarro et al. (2014) demonstrated that high-quality forage improves forage digestibility. According to a model by Benchaar et al. (2001), increased forage digestibility reduces enteric MP. This association between greater digestibility and reduced cattle gas emissions was also highlighted by Hegarty (1999).

Harper et al. (1999) observed less enteric MP when cattle were fed more digestible diets. These authors worked with the same animals in two different production systems (feedlot and grazing) and observed that while enteric MP in a feedlot system was between 57 – 66 g/day with diet digestibility ranging from 56 to 76%, the same animals emitted 213 – 232 g of enteric MP per day in a grazing system with diet digestibility ranging between 34 to 59%. Similar results were observed by Beauchemin and Mcginn (2005), who reported that enteric MP emissions decrease as the diet's digestibility increases.

Animal characteristics

Basarab et al. (2013) observed that independent of the production system (i.e., grazing or confinement), adopting a targeted approach in selecting animals based on specific traits has demonstrated a productivity improvement. These authors selected cattle based on their residual feed intake (RFI), a reference value used to assess the efficiency of feed utilization by cattle, where more efficient animals are characterized by low RFI values, indicating that they consume less feed than anticipated for maintenance and production purposes. Basarab et al. (2013) stated that selection based on the RFI can gradually improve feed efficiency and enteric MI.

Forage quality

Forage type and composition influence enteric MP in grazing systems (Archimède et al., 2011; Goel and Makkar, 2012; Guyader et al., 2014). According to Archimède et al. (2011), the forage composition can influence cattle's enteric MP, not only because of the chemical composition of the forage itself but also because of the different forage species in the pasture composition. According to Raghavendra et al. (2016), cattle grazing C3 grasses (also called C3 photosynthesis) produced less enteric CH_4 compared to C4 grasses (grasses that have C4 photosynthesis or C4 pathway). Moreover, cattle grazing legumes (C3 species) in warm climates produced 20% less enteric CH_4 than when consuming C4 (Saha and Butler, 2016).

Furthermore, individual forage components, such as tannins, can influence enteric MP. Tannins are secondary plant metabolites that may impact the fermentation process in the rumen by affecting the protozoa and bacteria (Goel and Makkar, 2012). The protozoa are microorganisms present in the rumen related to methanogenesis, with a positive linear relationship between the concentration of protozoa and the MP in the rumen, as these microbes produce CH_4 (Guyader et al., 2014). In a study by Woodward et al. (2001), cows being fed *Lotus corniculatus* (greater tannins concentration than the control) reduced their enteric MP by 23.7% g CH_4/kg of DMI when compared to cows being fed *Lolium perenne* silage (control, low in tannins). Moreover, Woodward et al. (2004) stated that dairy cows grazing *Lotus corniculatus* (forage with greater concentration of tannins) pasture had 17.7% less enteric MP than cows grazing *Lolium perenne* pasture. Moreover, Tiemann et al. (2008) observed that lambs fed with *Calliandra calothyrsus* and *Flemingia macrophylla* reduced the enteric MP. However, the reduction of emissions also reduced lambs energy and nitrogen retention, potentially because the legumes, rich in tannins, reduced the digestibility of dietary fiber, leading to reduced energy retention and reduced ruminal ammonia concentration, indicating a decrease in ruminal protein degradation (Tiemann et al., 2008).

Dietary additives

Dietary feed additives consist of different compounds that can be added to cattle diets to potentially reduce enteric MP. Some examples are ionophores (e.g., monensin) or unsaturated fats (Beauchemin and McGinn, 2006).

Monensin

Monensin is an ionophore that facilitates ionic transfer between some microbial populations' membranes (Pressman, 1976). Ionophores alter the biological membrane of the targeted microbes, causing an ion imbalance between the organism and its environment. The targeted microbes spend their energy trying to go back to balance, resulting in death and shifting the proportions of the different microbial populations in the rumen (Novilla, 2018). Van Nevel and Demeyer (1992) reported that monensin plays a significant role in altering the fermentation dynamics within the rumen. Specifically, the presence of monensin leads to an increase in the production of propionic acid. This process is crucial because propionic acid acts as a hydrogen sink in the rumen (Van Nevel and Demeyer, 1996). Hydrogen, which is necessary for propionic acid production, is utilized for propionic acid synthesis when monensin is present. This shift in hydrogen utilization has a secondary, beneficial effect because it reduces the availability of hydrogen for MP. Methane production in the rumen is a process that competes for hydrogen, which is a key element for its synthesis. Therefore, by increasing the proportion of propionic acid, monensin indirectly contributes to a reduction in MP from the rumen (Van Nevel and Demeyer, 1992; Van Nevel and Demeyer, 1995). Moreover, previous research has suggested that monensin also affects the population of some methanogenic bacteria, reducing the enteric MP in the rumen (Dellinger and Ferry, 1984). Therefore, adding monensin to a diet can reduce cattle's enteric MP, as was observed by Beauchemin and McGinn (2006), who concluded that adding monensin reduced the enteric MP without affecting diet digestibility.

Unsaturated fats

Blaxter and Czerkawski (1966) observed that adding unsaturated fats to sheep diets reduced enteric MP. Moreover, adding sunflower oil (1 to 3%) or Schizochytrium microalgae (1 to 2%) to the diet of ruminants decreases enteric MP (Elghandour et al., 2017). Unsaturated fats affect enteric MP in the rumen in different ways (reducing hydrogen available and modifying microbial population in the rumen) through a process called biohydrogenation. Biohydrogenation is when the unsaturated fat loses its double bonds, adding hydrogen to its structure and acting as a hydrogen sink, reducing the amount of hydrogen available to produce enteric CH_4 in the rumen (Jenkins, 1993). Lipids can also have toxic effects on ruminal microorganisms that impact enteric cattle MP (Byers and Schelling, 1993).

CONCLUSION

In summary, the literature review exposes significant gaps in understanding the relationship between production systems, dietary compositions, growth performance, and GHG emissions, particularly CH_4, in grazing cattle systems. Despite advancements in research, several critical areas remain understudied, highlighting the need for further investigation.

The review highlights the limited information on how different production systems and dietary compositions influence cattle growth performance and enteric GHG emissions. While some studies have examined these factors individually, there is a lack of comprehensive research that explores their combined effects. Future studies should aim to elucidate the dynamics between production systems, dietary components, and CH_4 emissions to optimize animal productivity and environmental sustainability.

Furthermore, the analysis reveals a lack of data on GHG emissions fluctuations across different cattle production phases. While some research has examined emissions in specific phases, such as grazing or confinement, there is a need for longitudinal studies that track emissions across multiple phases to capture the temporal variability. Understanding how GHG emissions fluctuate throughout the production cycle is essential for developing targeted mitigation strategies that address emissions hotspots and minimize environmental impact.

Moreover, the review emphasizes the importance of documenting cattle emissions across different phases of production. While some studies have measured emissions in specific phases, such as grazing or feedlot finishing, there is a lack of comprehensive data that measures the enteric GHG emissions across phases. By systematically measuring emissions at each stage of production, researchers can identify opportunities for emission reduction and develop strategies to mitigate the environmental impact of cattle production.

In conclusion, future research has a significant opportunity to address the remaining knowledge gaps, addressing the interplay between production systems, dietary compositions, growth performance, and GHG emissions in cattle systems.

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CHAPTER 2: EFFECTS OF ORIGIN ON STEERS ENTERIC METHANE EMISSIONS AND GROWTH PERFORMANCE

SUMMARY

The objective of the current study was to investigate enteric CH_4 emissions from yearling steers from different origins across different life stages. In Phase 1, steers were managed according to different management practices: extensive grazing in Colorado and confined backgrounding feeding in Nebraska and Wyoming. In Phase 2, all steers were grazed in the same location in Colorado. Average daily gain (kg/d) and CH_4 emissions were estimated throughout each phase of the study. During Phase 1, Nebraska steers had the greatest CH_4 production (MP; g/hd/d), while Colorado steers had the least. However, CH_4 intensity (MI; g of MP/ADG) was similar across all groups during Phase 1. In Phase 2, Colorado steers exhibited the greatest ADG and MP, with the least MI compared to Nebraska and Wyoming steers. Moreover, the current experiment explored how animals ranked according to their MI and MP between the two Phases. Animals from all origins experienced shifts in their classification, indicating the dynamic nature of MI and MP across different contexts. However, it was observed that Wyoming steers exhibited the most significant changes in the classification of MP (increased in their categories) when transitioning from a confinement system with grain-based diets to a grazing system. Evaluating and potentially being able to select low-emitter steers across all phases of their life may be an important tool for reducing MI and MP. The current study also evaluated different CH_4 prediction equations using different statistical approaches. Among the evaluated equations, three equations presented the potential to predict MP from steers accurately; however, more research has to be conducted to evaluate prediction MP equations in conditions similar to the current study. Overall, the current

study suggests that enteric CH_4 emissions were influenced by cattle's origin and previous management. This highlights the need for context-specific studies to accurately assess the sustainability and greenhouse gas (GHG) mitigation strategies for grazing beef cattle. Further research should address these variations to improve the accuracy of CH_4 emissions estimates in different rangeland ecosystems.

INTRODUCTION

Global warming results from an imbalance in the Earth's energy budget, where solar energy escaping the atmosphere is trapped by greenhouse gases (GHGs), such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), preventing it from radiating back into space (Watson et al., 1995; Denning, 2022). Notably, CH_4 has a 25 times Global Warming Potential (GWP) that is 25 times greater than CO_2 over a 100-year period. This means that CH_4 traps 25 times more heat in the atmosphere than an equivalent mass of CO_2 over that timeframe. Nitrous oxide has an even greater GWP, exceeding that of CO_2 by 273 times over a 100-year period, according to the Intergovernmental Panel on Climate Change (2023). This indicates that N_2O has a significantly greater impact on trapping heat in the atmosphere than CO_2. The increasing concentrations of GHG, primarily from sectors like electricity, transportation, industry, and agriculture, have significantly contributed to global GHG emissions, with the United States (US) alone accounting for 11% of the total global GHG emissions (Herzog, 2009; Jones et al., 2024).

In the US, the beef cattle production system sector is responsible for 10% of the country's total GHG and 35% of its CH_4 emissions (The Environmental Protection Agency, 2023). Enteric CH_4 is generated in the rumen of cattle as a hydrogen sink, produced by microbes fermenting feed in the rumen; therefore, the production of cattle enteric CH_4 is greatly influenced by cattle diet (Van Soest, 1982).

Moreover, the US beef production system includes grazing and confined animal systems. Usually, cattle go through both systems throughout their production cycle. Cow-calf operations are mainly based on grasslands (USDA – Economic Research Service, 2023), and calves produced in this system move around the country following two different paths: approximately 40% of post-weaning calves may go directly to a feedlot or confinement system, while approximately 60% of post-weaning calves may go to backgrounding (cattle gain more weight before the feedlot, raised on a diet that usually includes forage and grain) and stocking (cattle gain more weight before the feedlot, typically raised on pastures) systems before going to a feedlot (Drouillard, 2018).

Feedlot systems are concentrated in a few regions of the US, housing animals from different locations and backgrounds (USDA NASS, 2022 Census of Agriculture).

According to Harper et al. (1999), enteric GHG emitted by farm animals, particularly ruminant livestock, vary significantly between different production systems, such as grazing and feedlot systems. A preliminary study conducted by Raynor et al. (2024) suggested that local steers (from Colorado) exhibited greater growth performance and less CH_4 intensity (MI) compared to steers from other origins when all cattle were housed within the same grazing conditions in Colorado. Building on this hypothesis, we hypothesized that local animals (Colorado) would have greater growth performance and MI when compared to cattle from different origins (Wyoming and Nebraska). Therefore, the objectives of the current study were to document cattle emissions in different locations using different management practices and evaluate if their enteric emissions would be different or similar in the same location. Moreover, we aimed to explore how cattle would rank in MI and CH_4 production (MP) measurements between different phases of the production system and how previously developed CH_4 emissions prediction equations performed on predicting enteric CH_4 emissions from cattle in the current study.

MATERIALS AND METHODS

All procedures involving the use of animals were approved by the Institutional Animal Care and Use Committee (#4062). This experiment was conducted in two different phases. In Phase 1 (November 2022 to April 2023), cattle growth performance and enteric GHG emissions were measured from animals from different origins (Colorado, Nebraska, and Wyoming). In Phase

2 (May to July 2023), all animals were housed at the same location, and cattle growth performance and enteric GHG were measured simultaneously.

PHASE 1

Colorado steers

Study area

This study was conducted at a commercial farm operation at Nunn, Colorado, United States (40°54’36.36” N, 104°29’53.74” W). Cattle were in a single, moderately stocked 185-ha pasture dominated by *Bouteloua gracilis* (32%), *Hesperostipa comata* (27%), *Pascopyrum smithii* (14%), and other forage species (27%). Herbaceous biomass (forage) production, calculated using the methodology of Kearney et al. (2022), was estimated to be 1221 kg dry matter ha^{-1} (Table 1). Additional alfalfa hay (approximately 1% of BW/steer) was supplemented in the pasture daily.

Livestock

Forty mixed (22 black Angus cross, 14 red Angus cross, and four Hereford cross) yearling steers (initial body weight; IBW = 305 ± 22 kg, approximately 10 to 12 months old) were used in this phase from January 17th to March 15th of 2023 (57 d). Steers were individually weighed at the beginning (d 1) and at the end (d 57) of the study phase. A shrink adjustment of 4% was applied to each steer in all body weight (BW) measurements to estimate shrunk BW (SBW; Brownson, 2012). All steers were at the farm for a minimum of two days prior to the initial BW measurement. Forage composition was assessed every three weeks by collecting pasture (8 samples per day of collection) and hay samples (2 samples per day of collection). All forage samples were dried (65ºC for 72 hours), ground, and stored at room temperature until the end of the study for further analysis. Forage samples were composited by day of forage collection, and forage composition was analyzed using near-infrared (NIR) methodology. Average daily gain (ADG) was calculated by subtracting the final from the initial shrunk BW and dividing by the number of days of the study Phase.

Enteric gas emissions measurements

Enteric CH_4 emissions were estimated using the Automated Head Chamber System (AHCS; GreenFeed, C-Lock Inc., Rapid City, SD), which was placed adjacent to the pasture's water tank to encourage animal AHCS visitation. The AHCS is an automated system to monitor gas fluxes from the breath of individual ruminant animals. All individual animals were identified with a radio frequency identification (**RFID**) ear tags. Cattle were acclimated and had free access to the AHCS for 18 d prior to the collection period (39 d; February 4th to March 15th of 2023). Cattle were housed in a dry-lot pen receiving alfalfa hay as the sole feed source for the first three days of the acclimation before having access to the pasture to encourage acclimation. Once the collection period started, cattle were allowed a maximum of 6 AHCS visits per day, with a maximum of 6 bait pellet drops per visit (35 g per drop; 30 seconds between each drop). A three-minute minimum visit per animal was considered to represent a "good visit" that captures several eructation events from each cattle per single visitation to AHCS (Velazco et al., 2016)Cattle visits to AHCS that were less than three minutes were removed from the analyses, as were animals that did not have 15 visits or more (Gunter and Bradford, 2017). Enteric CH_4 production (MP; g/d) values were estimated using the average MP values for each time an animal visited the AHCS. Enteric CH_4 emission intensity (MI; g of CH_4/kg of ADG) was calculated for each animal using the average MP divided by ADG during the study Phase.

Nebraska steers

Study area

This study was conducted at the United States Meat Animal Research Center (USMARC), Clay Center, Nebraska, United States (40°31’24.43” N, 98°07’59.64” W). Cattle were fed a forage-based diet in a confined system (2 pens; 20 animals/pen, 41 by 14 m) (Table 1).

Livestock

Forty USDA MARC II yearling steers (IBW = 292 ± 23 kg, approximately 9 to 11 months old), born at the USMARC, Nebraska, were used in this Phase from February 13th to April 15th of 2023 (62 d). Steers were individually weighed at the beginning (d 1) and at the end (d 62) of the study. A shrink adjustment of 4% was applied to each steer in all BW measurements to estimate SBW. All steers were raised at the same farm prior to initial BW measurement was collected. After AHCS acclimation period, steers were assigned to two different dry-lot pens (20 animals/pen) where they remained for the rest of the experiment collection period. Cattle total mixed ration (TMR) was fed once a day in the morning (Table 1). Diet composition was assessed every three weeks by collecting fresh TMR samples. All feed samples collected in the study were processed and analyzed following the same procedures described in Colorado Phase 1.

Enteric gas emissions measurements

Enteric CH_4 emissions were estimated using the AHCS (GreenFeed, C-Lock Inc.) located inside a dry-lot pen. All individual animals were identified with an RFID ear tag. Before the cattle emissions measurement period began (45 d; March 1st to April 15th), all cattle were acclimated to the AHCS for 16 days. The 20 steers with greater AHCS visitation during the acclimation period were selected to be the Nebraska steers for the entire GHG emissions collection. The AHCS configuration was the same as in Colorado Phase 1, as well as the estimations of MP and MI. Steers with less than 55 visits to the AHCS were removed from the analysis (Renand and Maupetit, 2016).

Wyoming steers

Study area

This study was conducted at the Agricultural Research, Development, and Education Center (ARDEC), Fort Collins, Colorado, United States (40°39'12.46" N, 104°59'56.50" W). Cattle were fed a 45:55 forage to concentrate based diet (Table 1) and were housed in 45 by 16 meters pens.

Livestock

Forty Angus yearling steers (IBW = 191 ± 17 kg, approximately 7 to 9 months old), all born at the John E. Rouse Beef Improvement Center, Wyoming, were used in this phase from November 17th, 2022, to January 14th of 2023 (59 d). After weaning in Wyoming, all cattle were transported (218 km) to ARDEC three weeks prior to the initial of the study. Steers were individually weighed at the beginning (d 1) and at the end (d 59) of the study Phase using an extended silencer chute with a true test scale. A shrink adjustment of 4% was applied to each steer in all BW measurements to estimate SBW. All cattle were housed in the same pen, and diet was fed once a day in the morning (Table 1). All TMR feed samples collected in the study were processed as described in Colorado Phase 1. After samples were dry and ground, dietary samples from the current group of cattle were shipped and analyzed by the DairyOne laboratory. Cattle growth performance was calculated similarly to previously described in the Colorado Phase 1.

Enteric gas emissions measurements

Enteric CH_4 emissions were estimated using the AHCS located inside the confined pen. All 40 individual animals were identified with an RFID ear tag. Before the cattle emissions measurement period began (44 d; December 1st, 2022, to January 14th, 2023), all cattle were acclimated to the AHCS for 14 days. The automated head chamber system configuration was the same as in Colorado Phase 1, as well as the estimations of MP and MI. Steers with less than 55 visits to the AHCS were removed from the analysis (Renand and Maupetit, 2016).

PHASE 2

After the end of Phase 1 and before initiation of Phase 2, Colorado and Nebraska steers remained at the same location as in Phase 1, receiving the same management and nutrition for 60 and 36 days, respectively. However, Wyoming steers did not stay in the same location between the two Phases and were transported (187 km) from ARDEC to Eastern Colorado Research Center (ECRC) where they were fed a grain-based diet (51.0% Steam-flaked corn, 20.0% Triticale silage, 16.5% Dry distillers grain plus solubles, 6.0% Sorghum hay, and 6.5% vitamin and mineral supplement, % inclusion on dry matter basis) for 118 days in a confined system.

Study area

Phase 2 was conducted at the United States Department of Agriculture (USDA) − Agricultural Research Service (ARS) Central Plains Experimental Range (CPER), Nunn, Colorado, United States (40°50' N, 104°43' W). Cattle were allowed to graze in two moderately stocked pastures. Pasture 1 was grazed by all steers together for 50 days (from May 16th to June 22nd of 2023 and from July 18th to July 31st of 2023). All steers grazed pasture 2 for 26 days (from June 22nd, 2023, to July 18th, 2023).

Pasture 1 (96 hectares; 31% *Bouteloua gracilis*, 10% *Opuntia polyancantha*, 8% *Pascopyrum smithii*, 31% old standing dead species, and 21% other forage species; pasture forage composition was visually estimated by trained personnel). Herbaceous biomass (forage) production was calculated using the methodology of Kearney et al. (2022). The estimated biomass was 629 kg dry matter ha^{-1} at the beginning (May 16th), 1915 kg dry matter ha^{-1} at the middle of the experiment (June 20th), and 2125 kg dry matter ha^{-1} at the end of the experiment (August 3rd).

Pasture 2 (136 hectares; 39% *Pascopyrum smithii*, 16% *Sporobolus airoides*, 15% *Salsola iberica*, 8% *Atriplex canescens*, 7% *Chenopodium leptophyllum*, 7% *Bouteloua gracilis*, and 9% other forage species). The estimated biomass was 2345 kg dry matter ha^{-1} at the beginning (June 20th).

Livestock

Before the start of Phase 2, all steers used in Phase 1 were transported (CO = 26 km; NE = 630 km; WY = 175 km) to the same location prior to the initiation of Phase 2. Upon arrival, 60 steers (20 from each origin) from Phase 1 were chosen according to their AHCS visitation numbers (animals with greater AHCS visitation from each origin during Phase 1 were chosen) for Phase 2 of the current study. Therefore, 20 steers (IBW = 344 ± 30 kg) from Colorado, 20 steers (IBW = 378 ± 31 kg) from Nebraska, and 20 steers (IBW = 357 ± 19 kg) from Wyoming were used in Phase 2 from May 16th to July 31st of 2023 (77 d; Table 2). Steers were individually weighed at the beginning and end of the study Phase. All steers were received and acclimated to the farm for at least two days prior to BW initial measurement. A shrink adjustment (4%) was applied to each steer in all BW measurements.

Forage composition was assessed at the beginning, middle, and end of the experimental period by collecting pasture samples (8 samples per collection sample day). All forage samples were dried (65ºC for 72 hours), ground, and stored at room temperature until the end of the study for further analysis. Forage samples were composited by day of forage collection, and forage composition was analyzed using near-infrared (NIR) methodology. Average daily gain was calculated by subtracting the final from the initial shrunk BW and dividing by the number of days of the study Phase.

Enteric gas emissions measurements

Enteric CH_4 emissions were estimated using two AHCS (GreenFeed, C-Lock Inc.) placed adjacent to the pasture's water tank, and the cattle emissions measurement period lasted 77 days (May 16th – July 31st). All individual animals were identified with an RFID ear tag. Since cattle were previously exposed to the AHCS, no acclimation period was conducted during Phase 2. Cattle were allowed a maximum of 6 AHCS visits per day, with a maximum of 6 bait pellet drops per visit (35 g per drop; 30 seconds between each drop). A three-minute minimum visit per animal was considered to represent a “good visit” that captures several eructation events from each cattle per single visitation to AHCS (Velazco et al., 2016)Cattle visits to AHCS that were less than three minutes were removed from the analyses, as were animals that did not have 15 visits or more (Gunter and Bradford, 2017). Enteric MP (g/d) values were estimated using the average MP values for each time an animal visited the AHCS. Enteric MI (g of CH_4/kg of ADG) was calculated for each animal using the average MP divided by ADG during the study Phase.

RANKING AND RERANKING OF STEERS DURING PHASE 1 AND 2

Steers in the current experiment were ranked following two criteria: 1) Methane production and 2) Methane intensity. In each ranking criteria, steers were ranked independently in Phases 1 and 2 by their origin according to their individual MP or MI. Therefore, in Phase 1, a steer from Colorado, for example, was only compared to other steers from Colorado from Phase 1. Moreover, it was evaluated if steers changed their rank classification when moved from Phase 1 to Phase 2. Steers were classified according to their mean MP or mean MI in three different categories of CH_4 emitters during Phase 1: low (L; steers in the bottom 33% of MP or MI), intermediate (I; steers in the between 34 to 66% bottom to top of MP or MI), high (H; steers in the between 67 to 100% bottom to top of MP or MI). The same approach was conducted for the steers in Phase 2, where steers were classified according to their mean MP or mean MI in three different categories of CH_4 emitters: low (L; steers in the bottom 33% of MP or MI), intermediate (I; steers in the between 34 to 66% bottom to top of MP or MI), high (H; steers in the between 67 to 100% bottom to top of MP or MI). After the ranking of steers for Phase 1 and Phase 2 was conducted, it was evaluated if steers increased, decreased, or did not change their ranking category when moved from Phase 1 to Phase 2.

OBSERVED VS ESTIMATED ENTERIC CH_4 PRODUCTION

To assess the value of previously developed equations to estimate cattle MP compared to observed data collected in the current experiment, a comparison analysis was conducted between observed MP and previously developed equations to estimate MP (g/d; IPCC, 2006; Ellis et al., 2009; Moraes et al., 2014; Escobar-Bahamondes et al., 2016; Table 6). Moreover, a major variable required in the previously selected equations to estimate cattle MP is animal DMI. However, due to the absence of observed DMI, multiple previously developed equations to estimate DMI were used to estimate cattle DMI in the current experiment (Minson and McDonald, 1987; NRC, 1996;

IPCC, 2006; Galyean et al., 2011; NASEM, 2016); therefore, the MP predicted values are values generated from MP equations, using different results of DMI estimations as input. The prediction equations used in the current experiment are presented below:

Predicting CH_4 equations of forage-based diets:

Equation A (IPCC, 2006):

$$CH_4\ (g/d) = (GEI \times (Ym/100) \times 365)/55.65$$

Equation B (Ellis et al., 2009):

$$CH_4\ (g/d) = (2.68 - 1.14 \times (Starch/NDF) + 0.786 \times DMI)/\ 55.5 \times 1000$$

Equation C (Moraes et al., 2014):

$$CH_4\ (g/d) = (-\ 0.221 + 0.048 \times GEI \times 4.184 + 0.005 \times BW) \times 55.5 \times 1000$$

Equation D (Escobar-Bahamondes et al., 2016):

$$CH_4\ (g/d) = 71.5 + 0.12 \times BW + 0.10 \times DMI^3 - 244.8 \times fat^3$$

Where BW = Cattle SBW (kg), DMI = estimated DMI (kg/d), fat = fat inclusion in the diet (% dry matter basis), GEI = Gross energy intake (MJ/d), Starch = Estimated starch intake (kg/d), NDF = Estimated NDF intake (kg/d), and Ym = CH_4 conversion factor (% of GE in feed converted to CH_4; 6.5% was used grazing animals).

Predicting DMI equations:

Equation 1 (Minson and McDonald, 1987):

$$DMI\ (kg/d) = (1.185 + 0.00454BW - 0.0000026BW^2 + 0.315ADG)^2$$

Equation 2 (NRC, 1996):

$$\text{DMI (kg/d)} = \text{SBW}^{0.75} \times 0.002774 \times (\%\text{ CP in the forage}) - 0.000864 \times (\%\text{ ADF in the forage} + 0.09826)$$

Equation 3 (IPCC, 2006):

$$\text{DMI (kg/d)} = \text{SBW}^{0.75} \times ((0.2444\text{Nem} - 0.0111(\text{NEm}^2) - 0.472)/\text{Nem})$$

Equation 4 (Galyean et al., 2011):

$$\text{DMI (kg/d)} = 3.830 + 0.0143 \times \text{IBW}$$

Equation 5 (NASEM, 2016):

$$\text{DMI (kg/d)} = \text{MBW} \times 0.0225$$

Where: cattle BW = cattle SBW (kg), IBW = Cattle initial SBW (kg), MBW = middle BW (kg), ADG = ADG (kg/d), CP = Crude protein, ADF = Acid detergent fiber, NEm = estimated dietary net energy concentration of diet, MJ/kg. The equations by Ellis et al. 2009, and Moraes et al. 2014, had to be modified (adding /55.5 x 1000) as their results were in MJ/d, and for comparison reasons, all the results should be in the same unit (g/d).

The DMI estimated by the different equations (equations 1 to 5) was used as an input in each MP equation (equations A to D). Therefore, equation A, for example, had five different DMI estimations as input and, in consequence, five different MP estimations, being the result of A×1, A×2, A×3, A×4, and A×5 and resulting in 20 different equations. Moreover, the average of each of the five MP equations with all DMI equations was also estimated, estimating one MP value for each MP equation (A, B, C, D), for example, MP from equation A is the average of equations A×1, A×2, A×3, A×4, and A×5, subsequently for each equation. The MP from all equations was also estimated as equation ABCD, which is the average estimated from all previous equations. Resulting in 25 equations. Each MP predicting estimate from each equation was evaluated independently compared to observed values.

STATISTICAL ANALYSIS

ANOVA and Tukey Honest Significant Difference tests were conducted for statistical analyses performed using R (R Development Core Team, version 2024.04.1+748).

Animal growth performance variables (BW and ADG) were analyzed within each Phase (Phase 1 and Phase 2). The model was:

$$Y_{ij} = \mu + O_i + \varepsilon_{ij}$$

Where Y_{ij} = response variable; μ = overall mean; O_i = fixed effect of cattle origin (Colorado, Nebraska, or Wyoming in Phase 1 and Phase 2); e_{ij} = random error.

For the GHG emissions data (MP and MI), the statistical model was:

$$Y_{ijk} = \mu + O_i + MBW_j + \varepsilon_{ijk}$$

Where Y_{ij} = response variable; μ = overall mean; O_i = fixed effect of cattle origin (Colorado, Nebraska, or Wyoming in Phase 1 and Phase 2); MBW_j = mid body weight (average of initial and final body weight) of the steers and it was included as a covariate; ε_{ijk} = random error.

To assess the accuracy of each MP estimation, R^2, the Root Mean Square Error (RMSE; as a percentage and in kg), Mean Bias, and Slope Bias (%MSE), Mean and Slope Bias, and Concordance correlation coefficient analyses were conducted. The model used was:

$$Y_{ijk} = \mu + P_i + C_j + \varepsilon_{ijk}$$

Where Y_{ijk} = response variable; μ = overall mean; P_i = fixed effect of Phase; C_j = fixed effect of cattle classification (VL, L, I, H, VH); ε_{ijk} = random error.

Least square differences were generated and used to identify significant differences among variables. The tables display the least squared means, and statistical significance was declared significant at $P \leq 0.05$.

RESULTS

GROWTH PERFORMANCE

Phase 1

Colorado steers had the greatest ($P < 0.01$) IBW at the beginning of the experiment, being 4.5% heavier than Nebraska and 37% heavier than Wyoming steers (Table 2). Wyoming and Nebraska steers had over 34% greater ($P < 0.01$) ADG than steers from Colorado during the initial phase of the study when cattle were at different locations receiving different diets. At the end of Phase 1, Wyoming steers were almost 100 kg lighter ($P < 0.01$) than Colorado and Nebraska steers, which were similar to each other.

Phase 2

At the beginning of Phase 2, Nebraska steers had the greatest IBW, being 9.9% heavier ($P < 0.01$) than Colorado steers and 5.9% heavier than Wyoming steers (Table 2). Steers from Colorado had the greatest ($P < 0.01$) ADG and gained 41.0% more daily weight than the steers from Nebraska and 117% more than Wyoming steers. Moreover, Wyoming steers, which were the lightest group of cattle at the beginning of Phase 2 and had the least ADG during the same Phase, were also the lightest ($P < 0.01$) at the end of the study. The Colorado steers, who started lighter than Nebraska steers but had greater ADG, had a similar FBW to Nebraska steers at the end of the study.

ENTERIC METHANE EMISSIONS

Visitation to the automated head chamber system

Enteric GHG was not evaluated for all the steers in the current study. In Phase 1, enteric GHG data was collected for approximately 53% of all steers exposed to AHCS (21 of 40 Colorado steers, 20 of 40 for Nebraska, and in Wyoming 31 of 40; Table 3). Meanwhile, in Phase 2, approximately 72% of the steers exposed to AHCS had their enteric GHG data evaluated (17 of 20 Colorado steers, 12 of 20 steers from Nebraska, and 14 of 20 of the Wyoming steers). Growth performance characteristics from the animals for which GHG emissions were collected are summarized in Table 3. Overall, growth performance (ADG, IBW, FBW) from animals where MP was measured had similar values to their entire group (Table 2), regardless of the phase of the experiment.

Phase 1

Colorado steers emitted the least ($P < 0.01$) total MP in Phase 1, Wyoming steers were intermediate in MP, and Nebraska steers had the greatest total MP (Table 3). Although MP was different among groups of cattle during Phase 1, MI was not different ($P = 0.26$) among steers from Colorado, Nebraska, and Wyoming.

Phase 2

During the second phase of the experiment, when all cattle were in the same grazing pasture conditions, Colorado steers had the greatest ($P < 0.01$) MP, Wyoming steers had intermediate MP, and Nebraska steers had the least MP among steers origins (Table 3). However, despite not having the greatest total emissions per day, Wyoming steers had the greatest ($P = 0.05$) MI compared to Nebraska and Colorado steers, which were similar to each other.

RANKING AND RERANKING OF STEERS DURING PHASE 1 AND 2

When cattle ranking was evaluated based on MP from Phase 1 to Phase 2, 19 % of steers from Colorado increased their MP ranking category, while 17% from Nebraska increased, and 45% of all steers from Wyoming increased in their classification categories (Table 4). However, 25% of the steers from Colorado and Nebraska decreased their MP category, while 33% of Wyoming steers decreased in their MP category. Most Nebraska steers (58%) did not change their MP classification category from Phase 1 to Phase 2, as well as most of the steers from Colorado (56%), while about a quarter of the steers from Wyoming (22%) remained in the same MP categories during the two phases of the experiment.

When evaluating the MI ranking category of cattle transitioned from Phase 1 to Phase 2, 33% of steers from Nebraska increased in their MI category, alongside 25% from Colorado and 22% of steers from Wyoming (Table 5). Conversely, 45% of steers from Wyoming, 33% of the steers from Nebraska, and 31% of the steers from Colorado decreased in their MI ranking category. Almost half of Colorado steers (44%) maintained in the same MI classification category from Phase 1 to Phase 2, compared to a third of Wyoming and Nebraska steers (33% for both) that remained in the same categories throughout both phases of the experiment.

OBSERVED VS ESTIMATED CH_4 FOR BOTH PHASES

Model comparison and evaluation of previously developed equations to predict MP were conducted (Table 6). This analysis compared four previously developed cattle enteric MP equations (IPCC, 2006; Ellis et al., 2009; Moraes et al., 2014; Escobar-Bahamondes et al., 2016) in combination with five previously developed cattle DMI equations (Minson and McDonald, 1987; NRC, 1996; IPCC, 2006; Galyean et al., 2011; NASEM, 2016).

The current analysis revealed that the equation suggested by the "Intergovernmental Panel on Climate Change" (IPCC, 2006) was the CH_4 equation that often presented the least coefficient of determination (R^2) and Lin's concordance correlation coefficient (CCC; Table 6). The MP equation A, reported by IPCC (2006), using as an input the results of DMI equation 4, by IPCC (2006), was the equation (A×4) with the smallest R^2 and one of the smallest CCC, reporting the absence capacity of these equations together to precisely predict enteric MP in conditions evaluated in the current study. Moreover, Escobar-Bahamondes et al. (2016) published the most recent equation (equation D) evaluated in the current study. The results from their equations evaluation were not much greater than the results from the IPCC (2006) equations when using each DMI estimation equation, besides, when MP was estimated using the average of all DMI estimation equations as an input (equation D).

The MP equations that better predict CH_4 observed values from the current study were the MP equations B and C, developed by Ellis et al. (2009) and Moraes et al. (2014; Table 6). When the results of DMI equations 1, 2, 3, and 5 (Minson and McDonald, 1987; NRC, 1996; IPCC, 2006; NASEM, 2016) were used as an input in equations B and C, they often had the greatest, but still moderate, R^2 (evaluating a linear relationship). However, CCC decreased when the result of equation 3 was used as an input in equations B and C (B×3, C×3), which indicates a reduced agreement between observed and predicted MP values. Moreover, combinations with equation 2

(B×2, C×2) increased the mean bias of the predicted value. Overall, authors from the current study observed that the potential better equations to predict cattle enteric MP data from the current study are the combinations between the following equations: B×1, B×5, C×1, and C×5. Those were equations that presented overall greater R^2 and CCC, and smaller RMSE and mean bias. However, even though they had greater, but moderate R^2, both equations that used equation 1 to predict DMI (B×1 and C×1), had slightly greater slope bias suggesting that it can overestimate or underestimate actual observed values. Therefore, the best two equations to predict cattle enteric CH_4 emissions cattle in the current study were equations B×5 and C×5.

DISCUSSION

Based on a preliminary study conducted by Raynor et al. (2024) that suggested that local steers had greater growth performance and less MI compared to steers from different origins when all cattle were fed in the same grazing conditions in Colorado, the current study aimed to document cattle emissions and growth performance from steers from different origins and evaluate if these emissions would be different or similar for steers from different origins, production systems, and locations.

GROWTH PERFORMANCE AND METHANE PRODUCTION

Phase 1

The US beef production system comprises two main systems: grazing and confinement. While grazing systems are spread across the country, feedlot systems are concentrated in a few regions (USDA Economic Research Service, 2023). Most livestock will go through both systems (grazing and confinement) to finish their cycle (USDA Economic Research Service, 2023).

Therefore, it is crucial to understand the effects of transitioning cattle between these systems on MP and growth performance.

During the first phase of the current study, cattle from different origins were raised under different production management, which differed not only in their physical locations but also in the cattle breed composition, diet, and management. Although all animals were in a backgrounding production phase, the dietary regime that animals were under was greatly different (Table 1). Moreover, feed availability was not the same across cattle origins in Phase 1. Even though Nebraska and Wyoming cattle were housed in confined systems, where feed delivery was provided daily for an ad libitum intake, the diet fed in the two locations was not the same. Steers from Wyoming were receiving a diet with a greater concentrate-to-forage ratio (approximately 55:45), while Nebraska steers were receiving a diet with less concentrate-to-forage ratio (approximately 35:65). The difference in diet composition did not affect ADG between the two groups (Table 2). However, it may help explain the changes in MP observed between Nebraska and Wyoming cattle during Phase 1 (Table 3). Previous research has reported that cattle receiving greater forage concentrations in their diets would have greater total MP per day (Beauchemin and McGinn, 2005). However, grain-based diets decrease MP compared to a forage-based diet because grain-based diets usually have more rapidly digested components than forage-based diets, leading to greater production of volatile fatty acids and less MP (Johnson and Johnson, 1995). Moreover, greater ruminal fermentation may lead to a decrease in the ruminal pH, which will lead to a reduction in the methanogenic microorganisms' population, as they are affected by lower pH (Hegarty, 1999).

Although Colorado cattle received a 100% forage-based diet, those animals had the least total MP among cattle origins in Phase 1 (Table 3). As previously mentioned, greater fiber concentration would favor greater enteric MP. However, Colorado steers had the least ADG among cattle origins, indicating that those animals had the potential least feed intake among the groups. Moreover, despite the daily hay supplementation, Colorado animals were in a grazing system with limited forage availability, which may also have limited their daily feed intake and reduced MP and MI. According to Charmley et al. (2016), there is a single, strong, linear relationship between the MP and the DMI, as greater DMI will lead to an increase in material for fermentation in the rumen, leading to greater MP. Therefore, the potentially smaller DMI during Phase 1 would explain why animals in a 100% forage regime had the least MP. When all cattle were evaluated on MI, there was no difference among cattle origins, which is explained by the differences in cattle growth performance. Methane intensity takes into account productivity and efficiency, providing a more comprehensive understanding of the relationship between MP and cattle production. Therefore, focusing on MI rather than absolute MP enables a more refined assessment of the environmental sustainability of cattle production per unit of production. Consequently, as the MI is similar for all groups of steers, the environmental impact per kg of meat produced is the same for all the different cattle origins during the first phase of the current study.

Phase 2

In the United States, it is common for cattle to move across states when transitioning from one phase of the production system to another. According to Drouilard (2018), 60% percent of the animals in the US go through a backgrounding system. During the backgrounding system, it is common to receive cattle from different origins and comingle them into a similar environment and production system. One of the main questions of the current experiment was to observe how cattle from different origins (different previous backgrounds) would perform when placed in a similar production system. Moreover, how MP from those animals would behave when exposed to a different dietary regime and environment. Previous research conducted at the same location has suggested that cattle with different backgrounds would have different MP and growth performance after being placed at the same location (Raynor et al., 2024).

In the current study, the two groups (Nebraska and Wyoming) where animals were fed in a confined system in Phase 1 had a decrease in growth performance when placed in a grazing system. Moreover, the magnitude of this decrease was even greater in Wyoming steers compared to Nebraska steers. Between Phase 1 and Phase 2, Nebraska steers received a forage-based diet, while Wyoming steers received a grain-based diet for over 100 days before moving to the pasture for Phase 2. The dramatic change in cattle diet (grain to forage) and environment (confined to grazing) faced by Wyoming steers throughout the current study may explain the decreased growth performance of those animals during Phase 2. Although in a conventional production system, cattle are transitioned from pasture to grain, Purvis et al. (2011) reported that animals in a confined system in winter decreased their growth performance when moved to a grazing system during the spring.

Colorado steers, the only steers raised under grazing conditions during the entire study, had the greatest ADG during the second Phase of the experiment (Table 3). Moreover, Colorado steers also had the greatest MP among cattle origins. The greater growth performance and MP would indicate that those animals had the greatest DMI among cattle origins; moreover, it also suggests that those animals were used to the grazing environment, which would generate less stress in adapting to a new production system. Similar to the current study, Raynor et al. (2024) suggested that local steers had greater growth performance and MP than cattle that came from different states. Moreover, the fact that those animals had the least ADG during the initial phase of the study would also indicate a potential compensatory growth on Colorado steers when a greater quality diet was offered (Table 1). Colorado steers in the current experiment had greater ADG than usually expected for grazing animals in similar conditions. However, similar ADG to Colorado steers from the current study, have been reported in the same location by Irisarri et al. (2019). Those authors observed that in years classified as “wet” years, with annual precipitation greater than 259.1 mm, cattle had an ADG of up to 1.50 kg/d (Irisarri et al., 2019). These exceptional gains may be due to the exceptional forage availability of the current experiment (Table 1). Irisarri et al. (2019) reported forage availability between 375 to 1250 kg/ha from May to October, while the forage availability of the current experiment ranged between 629 to 2345 kg/ha, illustrating the unusually favorable year for cattle production in these semi-arid grasslands.

RANKING AND RERANKING OF STEERS

Over the years, selection for cattle with less CH_4 emissions has been proposed as a potential tool to mitigate GHG emissions in livestock production systems; therefore, classifying animals based on their CH_4 emissions would allow the industry to move forward in contributing to decreasing GHG emissions from beef cattle (Lassen and Løvendahl, 2016; Coppa et al., 2021; Beauchemin et al., 2022). The current study aimed to evaluate how steers from different origins changed their classification category based on their MI or MP from a previous backgrounding system to the same grazing production system. Methane, as MP and MI, ranking category among animals was accessed from 37 steers from different origins during an average of 134 days (78 days for Phase 2; and 57-, 58-, and 59 days during Phase 1 for Colorado, Wyoming, and Nebraska steers respectively). Cattle were classified in L, I, and H categories based on their MI and MP.

In the current study, Wyoming steers had major changes in their MP classification categories, which might be due to major changes in diet and environment to which those animals were previously exposed (Table 4). During Phase 1 and between the 2 phases, Wyoming steers were in a confined system receiving grain-based diets and were moved to a grazing condition with grass as the primary feed source during Phase 2. This major dietary change may have affected the ruminal microbial community, which may have affected the rumen fermentation parameters of those animals.

Changes in MI categories were similarly distributed across origins (Table 5). Colorado steers were the group that had more steers not changing their MI classification, compared to Nebraska and Wyoming steers. Colorado steers were grazing in a similar environment in both phases. In contrast, Wyoming and Nebraska steers had the greatest changes in their MI classification as 67 and 66 % of the steers increased or decreased their MI classification, which might be due to major changes in diet and environment to which those animals were previously exposed.

Goopy and Hegarty (2004) reported that the ranking of beef steers based on their MP would need to be determined according to cattle diet. These authors observed that steers were unable to maintain their CH_4 emission ranking (Low vs. High) when transitioning from a grain-based to a forage-based diet (Goopy and Hegarty, 2004). Beauchemin et al. (2022) reported minor changes in cattle ranking across different periods; however, animals were evaluated in a confined system and CH_4 yield was used as the ranking metric. Changes in MP parameters have also been previously reported when dairy cows were evaluated throughout the production cycle (Rischewski et al., 2017; Coppa et al., 2021). However, most of the previous research that has evaluated the ranking of cattle MP had access to individual DMI estimates (Rischewski et al., 2017; Coppa et al., 2021; and Beauchemin et al., 2022), which was not possible in the current study since animals were evaluated in a grazing system. As discussed by Beauchemin et al. (2022), the inconsistent results across research studies might be due to the different protocols used in each study; therefore, further research needs to be conducted to evaluate best practices and ensure that the selection of cattle based on their CH_4 are properly conducted.

OBSERVED VS ESTIMATED MP

Comparing observed MP data with estimates derived from various equations provides crucial insights into the accuracy and reliability of MP models in cattle production for the animals of this study. This comparison offers valuable information for assessing the performance of these models and their applicability in predicting CH_4 emissions under different conditions. However, it must be considered that many factors influence the MP from the animals. Digestibility of the diet (Hart et al., 2009), efficiency of feed utilization (Basarab et al., 2013), forage quality (Archimède et al., 2011; Goel and Makkar, 2012; Guyader et al., 2014), the presence of unsaturated fats in the diet (Jenkins, 1993) are crucial when determining MP. Moreover, one unique and crucial variable that enteric MP prediction equations often have in common is cattle DMI. However, one of the greatest challenges faced in grazing conditions is to estimate pasture intake by the animals grazing it.

Therefore, the current study decided to take an alternative approach in combining two equations that would estimate MP and DMI to predict observed enteric MP. Among the 20 combined equations evaluated, four equations stood out in terms of better predicting observed values (B×1, B×5, C×1, and C×5; Table 6). All four equations had similar RMSE, Mean Bias, and CCC. However, equations B×1 and C×1, which had the greatest R2, also had a slope bias that was, on average, almost four times greater than the slope bias produced by equations B×5 and C×5, which indicates that those last two equations would be the best-combined equations to predict values observed in the current study. Moreover, when evaluating the average of the different MP equations, as well as the average of all the MP equations together, two predictions have better performance than the rest, the average of all (ABCD; A = IPCC, 2006; B = Ellis et al., 2009; C = Moraes et al., 2014; D = Escobar-Bahamondes et al., 2016), and the average of equation D (Escobar-Bahamondes et al., 2016). Both equations had similar estimated mean, R^2, and mean bias. However, equation ABCD had smaller RMSE, slope bias, and greater CCC.

Although these equations are good estimation equations, there is room for improvement compared to the observed data. Perhaps considering more variables when estimating the MP or even developing new systems that predict MP with multiple on-farm inputs will be beneficial for estimating the MP accurately, a variable that is crucial for predicting the impact of beef production systems on the environment.

CONCLUSIONS

The current study reported enteric CH_4 production and growth performance of yearling steers from different origins. Colorado steers, which maintained the same location across phases, exhibited greater CH_4 production in Phase 2 compared to Nebraska and Wyoming steers, which underwent significant changes in their environment and diet ingredients. However, the steers from Colorado in Phase 2 exhibited less CH_4 intensity compared to steers from Wyoming due to superior growth performance. Transitioning steers between phases and environments led to notable shifts in their CH_4 ranking category within each origin, particularly evident in the MP of Wyoming steers who moved from confinement to grazing systems. This underscores the influence of diet and environmental factors on reranking outcomes, emphasizing the need for specific mitigation strategies according to individual production systems. Current enteric CH_4 prediction models, while potentially accurate for specific systems, reported limited efficacy in estimating CH_4

production for steers from the current study. Future research should refine these models to better capture diverse environmental contexts and steer characteristics, thus enhancing their predictive power and applicability.

TABLES

Table 1: Dietary ingredients during Phases 1 and 2.

Ingredient, % DM	Colorado Phase 1	Nebraska Phase 1	Wyoming Phase 1	Phase 2
Whole corn	-	-	32.7	
Dry distillers grains plus solubles	-	-	19.5	
Corn silage	-	69.0	18.8	
Alfalfa hay	49.0	31.0	12.7	
Wheat straw	-	-	11.0	
Vitamin and mineral supplement	-	-	3.8	
Supplement[1]			5.2	
Limestone	-	-	1.3	
Salt	-	-	0.1	
Forage (grazing)[2]	51.0	-	-	100.0
Nutrients analysis[3]				
DM (% of DM)	91.31	94.14	92.88	94.23
CP (% of DM)	12.16	14.35	10.37	15.57
NDF (% of DM)	62.41	47.53	45.82	51.97
ADF (% of DM)	40.91	31.47	29.06	29.72
TDN (% of DM)	59.20	66.06	65.50	67.04
NE_m (Mcal/kg)	1.28	1.50	1.55	1.54
NE_g (Mcal/kg)	0.71	0.91	0.96	0.94

[1] Supplement = 73% molasses-based vitamin and mineral supplement; 25% limestone; 2% salt.

[2] Colorado Phase 1 = 32% *Bouteloua gracilis*, 27% *Hesperostipa comata*, 14% *Pascopyrum smithii*, and 26% of other forage species with an estimated mass availability of 1221 kg DM/ha. Phase 2, pasture 1 = of Bouteloua gracilis (31%), Old standing dead species (31%), Opuntia polyancantha (10%), Pascopyrum smithii (8%), and other forage species (21%) with an estimated mass availability of 629 kg DM/ha at the beginning (May 16th), 1915 kg DM/ha at the middle of the experiment (June 20th), and 2125 kg DM/ha at the end of the experiment (August 3rd). *Phase 2, pasture 2 = Pascopyrum smithii (39%), Sporobolus airoides* (16%), *Salsola iberica* (15%), *Atriplex canescens* (8%), *Chenopodium leptophyllum* (7%), *Bouteloua gracilis* (7%), and other forage species (9%), with an estimated mass availability of 2345 kg DM/ at the beginning (June 20th).

[3] Nutrient analysis was performed using near-infrared spectroscopy for all groups except Wyoming, which was analyzed by Dairy One. DM = Dry matter; CP = Crude protein; NEm = Net energy for maintenance; NEg = Net energy for gain; NDF = Neutral detergent fiber; ADF = Acid detergent fiber.

Table 2: Cattle growth performance during Phases 1 and 2.

	Colorado	Nebraska	Wyoming	SEM	*P*-value
Phase 1[1]					
n (animals)	40	40	40		
IBW (kg)	305^{a}	292^{b}	191^{c}	3.6	<0.01
FBW (kg)	340^{a}	345^{a}	248^{b}	4.5	<0.01
ADG (kg)	0.62^{b}	0.89^{a}	0.98^{a}	0.060	<0.01
Phase 2[1]					
n (animals)	20	20	20		
IBW (kg)	344^{b}	378^{a}	357^{b}	6.9	<0.01
FBW (kg)	456^{a}	458^{a}	409^{b}	6.8	<0.01
ADG (kg)	1.48^{a}	1.05^{b}	0.68^{c}	0.056	<0.01

[a–c] Means within the same row without common superscript letters differ ($P < 0.05$).

[1] IBW = Initial shrunk body weight; FBW = Final body weight; ADG = Average daily gain (kg/d)

Table 3: Enteric CH_4 emissions and growth performance during Phases 1 and 2[1]

	Colorado	Nebraska	Wyoming	SEM	*P*-value
Phase 1[2]					
n (animals)	21	20	31		
AHCS (visits per animal)	33^c	189^a	103^b	7.2	<0.01
IBW (kg)	305^a	292^a	192^b	6.2	<0.01
FBW (kg)	350^a	352^a	250^b	7.0	<0.01
ADG (kg)	0.78^b	1.02^a	1.01^a	0.062	<0.01
MP (g/hd/d)	148.06^c	212.14^a	165.99^b	4.971	<0.01
MI (g CH_4/kg ADG)	231.71^a	213.36^a	169.61^a	35.094	0.26
Phase 2[2]					
n (# of animals)	17	12	14		
AHCS (visits per animal)	61^a	39^b	40^b	5.7	<0.01
IBW (kg)	339^b	370^a	356^{ab}	9.1	0.02
FBW (kg)	450^a	448^a	414^b	8.8	<0.01
ADG (kg)	1.46^a	1.03^b	0.75^c	0.059	<0.01
MP (g/hd/d)	252.24^a	205.66^c	220.08^b	7.289	<0.01
MI (g CH_4/kg ADG)	177.49^b	203.46^b	313.68^a	23.021	0.05

$^{a\text{-}c}$ Means within the same row without common superscript letters differ ($P < 0.05$).

[1] Variables for steers that MP was collected

[2] AHCS = Automated head chamber system; IBW = Initial shrunk body weight; FBW = Final body weight; ADG = Average daily gain (kg/d); MP = CH_4 production; MI = CH_4 intensity

Table 4: Animals that increased, decreased, or did not change their classification category based on CH_4 from Phase 1 to Phase 2.

	Colorado	Nebraska	Wyoming
Increased[1]	3 (19%)[2]	2 (17%)[2]	4 (45%)[2]
L - I	1	1	2
L - H	1	1	0
I - H	1	0	2
Decreased[1]	4 (25%)[2]	3 (25%)[2]	3 (33%)[2]
H - I	2	1	1
H - L	0	0	1
I - L	2	2	1
No Change[1]	9 (56%)[2]	7 (58%)[2]	2 (22%)[2]
H	3	3	1
I	3	2	0
L	3	2	1

[1] Animals were classified in ascending order based on CH_4 within phase and origin, and assigned to groups as low (1-33% of the animals), intermediate (34-66 % of animals), and high (67-100% of animals) emitters

[2] Percentage of steers, within origin, that increased, decreased, or did not change classification between Phase 1 and Phase 2.

Table 5: Animals that increased, decreased, or did not change their classification category based on CH_4 intensity from Phase 1 to Phase 2.

	Colorado	Nebraska	Wyoming
Increased[1]	4 (25%)[2]	4 (33%)[2]	2 (22%)[2]
L - I	0	2	0
L - H	3	1	2
I - H	1	1	0
Decreased[1]	5 (31%)[2]	4 (33%)[2]	4 (45%)[2]
H - I	2	1	2
H - L	2	1	0
I - L	1	2	2
No Change[1]	7 (44%)[2]	4 (33%)[2]	3 (33%)[2]
H	1	2	1
I	4	1	1
L	2	1	1

[1] Animals were classified in ascending order based on CH_4 intensity within phase and origin, and assigned to groups as low (1-33% of the animals), intermediate (34-66 % of animals), and high (67-100% of animals) emitters

[2] Percentage of steers, within origin, that increased, decreased, or did not change classification between Phase 1 and Phase 2.

Table 6: Model comparison and evaluation of predicted enteric CH_4 emissions across phases.

Prediction Equation[1,2]	Mean, g	R^2	RMSE[5], % Mean	RMSE[5], g	Mean Bias, % MSE	Slope Bias, % MSE	Mean Bias	Slope Bias	CCC[6]
Observed	194	-	-	-	-	-	-	-	-
ABCD[3]	199	0.37	19	37	2	15	-5	199	0.60
A[4]	269	0.29	45	88	73	11	-75	829	0.23
A×1	407	0.28	122	237	81	17	-213	9499	0.09
A×2	394	0.15	110	214	87	9	-200	4324	0.06
A×3	229	0.06	31	61	32	23	-35	870	0.18
A×4	160	0.26	26	50	47	0	34	0	0.28
A×5	154	0.37	27	53	57	4	40	117	0.40
B[4]	171	0.37	21	41	32	0	23	0	0.45
B×1	200	0.36	22	42	2	34	-6	591	0.59
B×2	160	0.40	24	47	53	0	34	2	0.38
B×3	136	0.40	35	68	72	3	58	130	0.12
B×4	156	0.17	28	54	49	0	38	13	0.14
B×5	203	0.30	20	38	5	10	-9	152	0.52
C[4]	156	0.39	26	50	58	0	38	1	0.36
C×1	187	0.38	22	43	3	38	8	715	0.59
C×2	144	0.43	31	59	71	0	50	1	0.29
C×3	119	0.38	43	83	82	2	75	156	0.09
C×4	140	0.22	34	66	67	1	54	33	0.11
C×5	189	0.32	19	37	2	12	5	173	0.56
D[4]	200	0.34	25	49	2	50	-6	1202	0.55
D×1	279	0.30	88	171	25	71	-85	20615	0.21

D×2	168	0.41	22	43	39	3	27	50	0.50
D×3	135	0.20	36	71	71	1	60	57	0.08
D×4	157	0.14	28	54	48	0	37	0	0.15
D×5	264	0.31	53	102	46	42	-70	4435	0.28

[1] Estimated CH_4: A = IPCC (2006); B = Ellis et al. (2009); C = Moraes et al. (2014); D = Escobar-Bahamondes et al. (2016)

[2] Estimated DMI: 1 = Minson and McDonald (1987); 2 = NRC (1996); 3 = IPCC (2006); 4 = Galyean et al. (2011); 5 = NASEM (2016).

[3] Average of all MP equations using as input all DMI estimation equations

[4] Average of each MP equation, using the results of the different DMI estimation equations

[5] Root Mean Square Error

[6] Concordance correlation coefficient

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CHAPTER 3: CONCLUSIONS

CONCLUSIONS

Exclusively focusing on MP in the current study of yearling steers from different origins would have presented an incomplete picture. Steers that did not drastically changed their location and diet across study Phases (Colorado steers) exhibited greater MP than steers that had major changes their location and production system across Phases (Nebraska and Wyoming steers); however, local steers had greater growth performance resulting in less MI. While the absolute MP was less for Nebraska and Wyoming steers, their underperformance in the semi-arid rangeland settings decreased the viability of an economically competitive stocker cattle operation.

Steers from various origins undergo changes in their ranking and reranking based on MI when transitioning between phases and production environments. Notably, animals from all origins experienced shifts in their classification categories, indicating the dynamic nature of MI across different contexts. However, it was observed that steers from the Wyoming group exhibited the most significant changes in classification categories when transitioning from a confinement system with grain-based diets to a grazing system. This suggests that alterations in diet characteristics and environmental conditions are crucial in driving reranking outcomes. The findings underscore the importance of considering these factors when assessing MI and implementing strategies to mitigate greenhouse gas emissions in beef production systems. Further research is warranted to elucidate the underlying mechanisms driving reranking dynamics and to refine MP prediction models for improved accuracy and applicability across diverse production environments.

The estimation models for MP may be accurate for some systems with specific characteristics. However, most models were not accurate when estimating the MP of the steers of the current study. Future research could focus on improving these models' accuracy and predictive capabilities by incorporating additional variables or refining the underlying algorithms based on more extensive and diverse datasets.