DISSERTATION

EVALUATION OF CATTLE SUB-SPECIES ON GROWTH PERFORMANCE AND GAS FLUX AND THE COMPARISON OF PREDICTION MODEL ACCURACY AND AGGREGATION TO ESTIMATE ENTERIC METHANE EMISSIONS OF FINISHING BEEF STEERS

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ABSTRACT

EVALUATION OF CATTLE SUB-SPECIES ON GROWTH PERFORMANCE AND GAS FLUX AND THE COMPARISON OF PREDICTION MODEL ACCURACY AND AGGREGATION TO ESTIMATE ENTERIC METHANE EMISSIONS OF FINISHING BEEF STEERS

Over the past several decades, extensive research has focused on quantifying the environmental impact of beef production and developing strategies to mitigate enteric methane (CH_4) emissions. Two experiments were conducted to study growth performance, enteric CH_4 production, and carcass characteristics of *Bos indicus* and *Bos taurus* steers managed with and without the use of growth-promoting technology. Following the completion of the field research outlined in experiments 1 and 2, data was compiled across numerous beef finishing experiments, including experiments 1 and 2, to generate a database to evaluate the accuracy of enteric CH_4 prediction models.

In the first experiment, the objectives of the study were to evaluate the comparative growth performance, carcass characteristics, and gas flux of yearling Bos indicus (BI; Brahman) and Bos taurus (BT; Angus) steers managed with (TRT) and without (CON) the use of growth-promoting technology (GPT). One hundred BI (initial body weight (IBW) = 342 ± 31 kg) and 100 BT (IBW = 341 ± 21 kg) steers were fed for 180d in 2 consecutive phases. In Phase 1, d 0-83, cattle of each sub-species were blocked by body weight and randomly assigned to a management treatment in 10-hd research pens (5 pens/treatment). In Phase 2, d 84-180, cattle were moved and randomly

assigned to a 50-hd research pen (1 pen/treatment) equipped with 1 GreenFeed automated head chamber system (C-Lock, Rapid City, SD, USA) and 5 SmartFeed bunk systems (C-Lock, Rapid City, SD, USA) for measuring individual gas flux of CH_4, carbon dioxide (CO_2), oxygen (O_2), and hydrogen (H_2) and feed intake, respectively. Data were analyzed with R (R Core Team, 2021, v. 4.4.1) software to assess the fixed effects of cattle sub-species, treatment, and their interaction for growth performance collected in Phase 1 and 2, and gas flux which was only measured in Phase 2. In phase 1, IBW did not differ ($P > 0.75$) by sub-species or treatment. Dry matter intake (DMI), average daily gain (ADG), and feed efficiency (G:F) were greater ($P < 0.01$) for BT, resulting in greater final body weight (FBW) for BT compared to BI. Within sub-species, DMI did not differ ($P > 0.35$) between treatments in Phase 1, but ADG, G:F, and FBW were greater ($P < 0.01$) for TRT compared to CON. In Phase 2, DMI increased with the use of GPT. However, there was a sub-species × treatment interaction ($P \leq 0.04$) where greater increases in ADG and FBW were observed between TRT and CON for BT relative to BI. Furthermore, BI had a greater proportion of Standard and Select quality grades relative to BT. Daily CH_4 production (g CH_4/d), CH_4 yield (g CH_4/kg DMI), and yield of CH_4 (% of gross energy intake) were less ($P < 0.01$) for BI than BT. The use of GPT decreased emissions intensity per unit ADG and carcass gain; furthermore, a sub-species × treatment interaction existed ($P \leq 0.05$), where a greater decrease in EI was observed between CON and TRT for BT when compared to BI. Ultimately, BT had greater growth performance and carcass quality, but BI emitted less CH_4, highlighting the complex tradeoffs resulting from sustainability-related research in beef production systems.

In the second experiment, the study objectives were to evaluate the comparative growth performance, carcass characteristics, and gas flux of yearling BI (Brahman) and BT (Angus) steers managed with (GPT+) and without (GPT-) the use of GPT in winter conditions. One hundred BI

(IBW = 364 ± 22 kg) and 100 BT (IBW = 323 ± 17 kg) steers were fed for 180 d in two consecutive phases. In Phase 1, d 0-83, steers of each sub-species were blocked by IBW and randomly assigned to a treatment (10 hd/pen, 5 pens/treatment). In Phase 2, d 84-180, steers were moved to Climate Smart Research Pens where each treatment was randomly assigned to a research pen equipped to measure individual feed intake and gas flux (50 hd/pen, 1 pen/treatment). Data were analyzed with R (R Core Team, 2021, v. 4.4.1) software to assess the fixed effects of cattle sub-species, treatment, and the sub-species × treatment interaction. In Phase 1, IBW differed ($P < 0.01$) by sub-species, but did not differ ($P = 0.98$) by treatment. The DMI, ADG, and G:F were greater ($P < 0.01$) for BT, resulting in greater FBW for Phase 1. Within sub-species, DMI, on a total daily basis and as a percentage of body weight, did not differ ($P \geq 0.09$) between treatments in Phase 1, but ADG, G: F, and FBW were greater ($P \leq 0.04$) for GPT+ than GPT-. In Phase 2, G:F and DMI when represented on a total daily and as a percentage of BW basis had a sub-species × treatment interaction ($P \leq 0.04$) where greater increases in G:F and DMI were observed between GPT+ and GPT- for BI than for BT. Steers managed with GPT and BT steers had greater ($P \leq 0.01$) ADG and FBW. Calculated yield grade and backfat thickness were greater ($P < 0.01$) for BT steers, and BT had more ($P < 0.01$) USDA Choice and Prime quality grades than BI. Longissimus muscle area was greater ($P < 0.01$) for BT and GPT+ steers. Daily CH_4 emitted was less for BI steers; however, CH_4 as a proportion of DMI and gross energy intake were less ($P < 0.01$) for BT steers. There was a sub-species × treatment interaction ($P < 0.01$) for CH_4 per unit ADG, where a decrease was observed between GPT- and GPT+ for BI, while no difference was observed for BT. In conclusion, BT had greater growth performance and carcass quality, but observations differed by cattle sub-species when CH_4 was reported on an absolute versus yield or intensity basis.

Following the completion of the second study, data across 7 beef finishing experiments from 2023-2025 were compiled to create a database for analysis. The objective of this study was to determine the accuracy and precision of estimated enteric CH_4 production generated by different aggregations of prediction models compared to observed CH_4 emissions of finishing beef steers fed a concentrate-based diet. This study evaluated the accuracy and precision of 66 published enteric CH_4 prediction models and eight aggregations against observed CH_4 emissions from finishing steers fed a concentrate-based diet across seven independent experiments. Data were stratified into three databases: the full database (n = 888), *Bos taurus* database (n = 755), and *Bos indicus* database (n = 133). Prediction model performance was assessed using root mean square prediction error (RMSPE), concordance correlation coefficient (CCC), and decomposition of RMSPE into mean bias (MB), slope bias (SB), and residual bias (RB). Model aggregations were constructed based on weighted rankings derived from these metrics. Across all databases, aggregation approaches A1-A7 reduced RMSPE compared to most single model evaluations and produced CH_4 estimates within ±10% of the observed mean. However, the aggregation utilized by the Beef Cattle Nutrient Requirements Model (NASEM) consistently underpredicted CH_4. The top-performing aggregated models consistently incorporated DMI as a predictor, emphasizing the influence that feed intake has on CH_4 production. Despite improvements in overall prediction error, residual slope bias, especially for the *Bos indicus* database, and slight to moderate CCC values, according to criteria established by Proctor et al. (2024), indicate that further refinement is necessary to achieve high accuracy at the individual-animal level. These findings demonstrate that model aggregation offers a pragmatic and effective strategy for enhancing predictive performance of enteric CH_4 emissions in finishing beef steers, supporting improved GHG inventories, life cycle assessments, and mitigation strategies in beef production systems. However, continued development of robust prediction models will depend on sustained direct measurement of enteric CH_4 emissions, necessitating increased investment in research and methodological development.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1- REVIEW OF LITERATURE

INTRODUCTION

Atmospheric greenhouse gas (GHG) concentrations have increased since the industrial revolution resulting in increased average global temperature, greater variability in temperature and precipitation extremes, and more frequent severe weather events (Masson-Delmotte et al., 2021; Reidmiller et al., 2018). As a result, agricultural commodities are experiencing heightened vulnerabilities due to projections of greater inter- and intra-annual climate variability. Temperature increases, longer and more intense drought periods, and more extreme precipitation events, will present challenges for agricultural production throughout the United States (U.S.) (Steiner et al., 2017). Agricultural vulnerabilities due to climate change have necessitated support in identifying and developing adaptation strategies that are commodity-specific. Moreover, exposure to the synergistic effects of warming, such as fewer and more intense precipitation events and greater overall weather variability, will uniquely affect livestock production systems (Cook et al., 2022; Godde et al., 2021). Drought, variation in precipitation, and rising temperatures are primary climate concerns for the U.S. beef industry due to impacts affecting forage availability and quality, water supply, and associated heat and cold stress that may be experienced by cattle (Polley et al., 2013; Ojima et al., 2015; Briske et al., 2021).

A growing interest exists to better understand the interaction between livestock production and climate change. A foundational step in developing strategies to mitigate the environmental impacts of U.S. beef cattle production is to comprehensively evaluate the dynamic relationship between climate change and beef production systems, including the risks that a changing climate poses to production and the sector's contributions to a changing climate. Secondary steps include isolating where gaps in knowledge exist. Identifying knowledge gaps can be further used to inform practical research with scalable potential. The purpose of this review is to 1) assess the interaction between beef cattle production and climate change and 2) understand factors influencing animal efficiency and the environmental impact of beef cattle.

Greenhouse gas production in U.S. beef cattle production systems

Heightened national and global attention regarding the role of anthropogenic GHG emissions in climate change, coupled with population growth and increasing competition for finite resources, has intensified pressure across every industry to reduce environmental impacts (van Beek et al., 2010; Rotz et al., 2019). In cattle production systems specifically, the importance of feeding the growing population while minimizing the environmental impacts of cattle production has been given significant attention throughout the 21st century (Steinfeld et al., 2006; Golub et al., 2012; Eisler et al., 2014). In addition to growing populations, increases in per capita meat consumption globally have been predicted (Alexandratos and Bruinsma, 2012). Adding to the complexity of this challenge, the quantification of the sustainability of the U.S. beef industry is challenging because the supply chain is one of the most multifaceted agri-food systems in the world (Rotz et al., 2019). Therefore, there is a need to enhance productivity in an environmentally sustainable manner while also considering the complexity of the U.S. beef supply chain (Rotz et al., 2019).

Beef cattle production contributes to GHG emissions, specifically methane (CH_4) and nitrous oxide (N_2O; Stackhouse et al., 2011). Methane is a potent GHG, despite being short-lived, that has a global warming potential over a 100-year time horizon of 28 times that of carbon dioxide (CO_2; Masson-Delmotte et al., 2021). The majority of enteric CH_4 is produced as a by-product of fermentation in the rumen, where microbial digestion enables cattle to convert complex carbohydrates into human-edible protein (i.e., beef; Patra, 2011; Knapp et al., 2014). Among domestic livestock, beef and dairy cattle are the primary contributors to enteric fermentation emissions (EPA, 2024). However, despite decades of research on CH_4 mitigation, many proposed strategies have demonstrated limited scalability to date, and minimal research has been done in production environments to assess commercial viability. Therefore, reducing CH_4 from enteric fermentation represents a significant need and opportunity for beef production systems.

In 2022, total U.S. GHG emissions were 6,343.2 million metric tons of carbon dioxide equivalent (MMT CO_2 eq), of which the agriculture sector contributed 593.4 MMT CO_2 eq, representing 9.4 percent of national emissions (EPA, 2024). Methane is a dominant component of agricultural emissions, totaling 276.8 MMT CO_2 eq, with enteric fermentation and manure management accounting for 192.6 and 64.7 MMT CO_2 eq, respectively (EPA, 2024). Enteric fermentation alone comprised 27.4 percent of total anthropogenic CH_4 emissions and 32.5 percent of agriculture sector emissions, demonstrating the substantial contribution of enteric fermentation as a CH_4 source (EPA, 2024). In 2022, cattle remained the dominant source of CH_4 from enteric fermentation in the U.S., with beef cattle contributing approximately 137 MMT CO_2 eq (~71 percent) and dairy cattle contributing 48.9 MMT CO_2 eq (~25 percent) (EPA, 2024). Although CH_4 emissions from enteric fermentation increased by 5.2 percent between 1990 and 2022, CH_4 emissions declined by 2 percent from 2021 to 2022, largely due to a reduction in the beef cattle population, highlighting the significant influence of herd size on CH_4 emissions trends in the U.S. (EPA, 2024).

Life cycle assessment as a methodology for quantifying the carbon footprint of beef cattle

Life cycle assessment (LCA) is a widely accepted methodology for quantifying the carbon footprint and broader environmental impacts of beef cattle production systems, as it integrates emissions and resource use across the full production life cycle- from raw material extraction and feed production to cattle management, transport, and product output (Rotz et al., 2010; Dillon et al., 2021; Putman et al., 2023). Beef production systems are inherently complex, involving biological processes, region-specific management strategies, and multiple production phases, which makes direct measurement of GHG emissions impractical at scale (Rotz et al., 2010; Stackhouse et al., 2011). The ability to utilize LCA addresses this challenge by combining empirical data, process-based models, and standardized global warming potential (GWP) multipliers to express emissions as CO_2 eq, allowing emissions from CH_4, N_2O, and CO_2 to be compared on a common basis (Heflin et al., 2019). Global warming potential is a measure of how much energy the emission of 1 MT of a gas will absorb over a given period of time, relative to the emission of 1 MT of CO_2. Despite recognized limitations related to data availability, uncertainty, and spatial and temporal variability, LCA remains the best available tool for assessing net GHG emissions from beef production systems and evaluating enteric methane emissions within a systems-level context (Dillon et al., 2021).

Beef cattle are typically produced through interconnected phases (i.e., cow-calf, stocker/backgrounding, and finishing) where each contributes differently to total emissions and resource use (Rotz et al., 2019; Werth et al., 2021). Across multiple LCA studies, the cow-calf phase consistently represents the largest share of total GHG emissions in the beef cattle production sector, largely due to animal maintenance requirements of the cow herd and the utilization of roughage-based diets which increase enteric methane production. Rotz et al. (2019) estimated that approximately 77 percent of enteric fermentation emissions occur during the cow-calf phase, with 74 percent of total lifetime feed intake consumed during this stage. Similarly, Stackhouse-Lawson et al. (2012) reported that the cow-calf phase accounted for 69-72 percent of total GHG emissions in a California-based beef system utilizing British cattle. In contrast, the finishing phase, while shorter in duration, is resource-intensive and contributes disproportionately to fossil energy use, reactive nitrogen losses, and ammonia emissions, accounting for approximately 15 percent of total GHG emissions but 30 percent of fossil energy use and 35 percent of ammonia emissions (Rotz et al., 2019). These observations illustrate the importance of evaluating emissions across all life cycle stages rather than focusing solely on a particular production system in a specific phase.

Life cycle assessments consistently report substantial variability in the carbon footprint of beef, reflecting differences in system boundaries, functional units, regional conditions, and management practices (Table 1; Werth et al., 2021). Using carcass weight (CW) as a functional unit, Rotz et al. (2019) reported an average carbon footprint of 23.3 kg CO_2 eq/ kg CW across U.S. beef systems, with values ranging from 17 to 40 kg CO_2 eq/ kg CW, while regional analyses in the Southwest yielded smaller numeric averages near 20.2 kg CO_2 eq/ kg CW. Comparable studies report similar ranges, with Stackhouse-Lawson et al. (2012) estimating 10.7 to 22.6 kg CO_2 eq/ kg CW depending on management strategy, and Putman et al. (2023) reporting 21.0 kg CO_2 eq/ kg CW for a partial, cradle-to-farm gate LCA. When Putman et al. (2023) expanded the scope of the LCA to a full value-chain assessment, the global warming potential nearly doubled to 42.7 kg CO_2 eq/ kg of consumed beef, highlighting the influence of downstream processing, transport, and retail stages. These differences underscore the need for transparent system boundaries and standardized functional units when comparing LCA outcomes.

Across beef LCAs, enteric methane is consistently identified as one of the single greatest contributing factors to the carbon footprint (Rotz et al., 2013; Cusack et al., 2020; Putman et al., 2023). No single emission source overwhelmingly dominates total emissions; however, carbon footprints are moderately sensitive to changes in enteric CH_4, making it the most impactful target for future mitigation (Rotz et al., 2019). Studies indicate that increased cattle production efficiency, such as improved feed quality, optimized supplementation, and genetic selection, can reduce emission intensity by producing more beef per unit of GHG emitted (Vergé et al., 2008; Heflin et al., 2019; Cusack et al., 2020). Feed production and upstream resource use also contribute substantially to emissions, particularly in finishing systems where concentrate-based diets can account for over 80 percent of feed-related GHG emissions (Werth et al., 2021). While land-based carbon sequestration and efficiency strategies show promise, results vary regionally, and high baseline efficiencies in U.S. systems may limit further reductions (Cusack et al., 2020). Ultimately, LCA provides a critical framework for identifying realistic mitigation opportunities while accounting for trade-offs across the full beef production system.

Improvements in efficiency have reduced the carbon footprint of beef production

Improvements in production efficiency have played a central role in reducing the carbon footprint of beef cattle systems over recent decades, primarily by decreasing GHG emission intensity per unit of beef produced. Vergé et al. (2008) reported a decline in the carbon footprint of beef production from 16.6 kg CO_2 eq/ kg body weight (BW) in 1981 to 10.0 kg CO_2 eq/ kg BW in 2006, representing an approximate 40 percent reduction. This improvement was largely attributed to a structural shift from extensive pasture-based systems toward more intensive feedlot production, where more grain-based and less roughage-based diets have reduced enteric methane emissions and improved cattle growth rates. Increased production efficiency has allowed greater quantities of beef to be produced from fewer animals, thereby decreasing emission intensity. The use of emission intensity metrics enabled the methane-mitigating benefits of feedlot systems to be identified without being obscured by concurrent increases in cattle numbers (Vergé et al., 2008). Importantly, observations of Vergé et al. (2008) also highlight that while production efficiency is a critical driver of emission reductions, decreases in GHG intensity cannot be attributed solely to efficiency gains, as dietary composition and system management also impose significant influence.

Comparisons of historic and modern beef production systems further demonstrate the role of efficiency in reducing environmental impacts across multiple resource categories. Capper (2011) reported that modern U.S. beef production systems, modeled using 2007 industry data, required substantially fewer inputs than systems in 1977 to produce an equivalent quantity of beef, including 69.9 percent of the animals, 81.4 percent of feedstuffs, 87.9 percent of water, and 67.0 percent of land. These efficiency gains were accompanied by proportional reductions in outputs, with modern systems producing 81.9 percent of the manure, 82.3 percent of CH_4, and 88.0 percent of N_2O relative to 1977 systems. Collectively, these changes resulted in a 16.3 percent reduction in the carbon footprint of beef production over the 30-year period (Capper, 2011). These observations elucidate the effectiveness of strategies to increase production intensification, such as improved genetics, nutrition, and management, in lessening the carbon footprint of beef on an intensity basis.

Despite these demonstrated benefits, reliance on efficiency gains alone presents limitations for achieving future climate objectives. Evidence suggests that biological and technological constraints may limit further increases in beef yield per animal, indicating that efficiency improvements may approach a plateau in mature production systems (Capper, 2011). Moreover, emerging national and global climate targets increasingly emphasize absolute reductions in GHG emissions across entire supply chains, rather than solely reductions in emission intensity. Consequently, while efficiency improvements have been instrumental in reducing the carbon footprint of beef cattle production, future mitigation efforts will likely require complementary strategies that extend beyond production efficiency, including innovations in enteric methane mitigation, resource management, and system-wide emissions accounting to achieve sustained and meaningful reductions in total GHG emissions.

Production practices influence efficiency and environmental outcomes of beef production

Sustainable development has been described as meeting present needs without compromising the ability of future generations to meet their own (Brundtland, 1987). Within beef production, sustainability is situated at the intersection of environmental stewardship, economic viability, and social acceptability (Capper, 2012). Over the past several decades, advancements in nutrition, genetics, and management have markedly improved production efficiency. Since 1977, the U.S. beef industry has reduced its overall carbon footprint by 16 percent while using 19 percent less feed, 12 percent less water, and 33 percent less land per unit of beef produced (Capper, 2011). Furthermore, it should be noted that the assessment by Capper (2011) was conducted over a decade ago, and advancements are likely given changes in cow herd dynamics with sustained beef production. These improvements have enabled the production of affordable beef while simultaneously reducing resource use and GHG emissions per unit of product (Lawrence and Ibarburu, 2007; Capper and Hayes, 2012).

Despite measurable efficiency gains, certain modern production practices, particularly finishing cattle in feedlots and the use of growth-promoting technology, are sometimes viewed unfavorably by consumers due to concerns related to animal welfare, human health, or environmental sustainability (Anderson et al., 2001; Harrington and Lu, 2002; MacArthur et al., 2006; Fraser et al., 2008). However, comparative system analyses consistently demonstrate that conventional beef production systems, which utilize confined finishing systems (i.e., feedlot) and growth-promoting technology, require fewer animals and less land, water, feed, and fossil fuel inputs per unit of beef than “natural” systems that exclude these technologies (Capper, 2012).

Improved growth performance of beef cattle, which can be achieved via the use of growth-promoting technology, is suggested to be one of the most effective mitigation strategies to decrease GHG emissions from beef production per unit of feed consumed and product produced (Boadi et al., 2004; Monteny et al., 2006; Capper and Hayes, 2012; Stackhouse et al., 2012).

Systems modeling conducted by Capper (2012) showed that cattle managed with growth-promoting technology achieved greater slaughter weights with fewer days on feed, thereby reducing the total number of cattle required to produce a fixed quantity of beef. In contrast, natural production systems were associated with a 17.4 percent increase in carbon emissions, greater manure output, and increased nitrogen and phosphorus excretion. As global demand for beef rises alongside pressure to reduce environmental impacts, strategies that enhance animal productivity are increasingly recognized as central to sustainable beef production.

Growth-promoting technologies and beef cattle efficiency

The livestock sector faces the dual challenge of increasing food production while reducing reliance on land, water, and energy resources (Capper and Hayes, 2012). Growth-promoting technology approved for use in the U.S. by the Food and Drug Administration (FDA), including anabolic implants, ionophores, melengestrol acetate, and beta-adrenergic ligands, play a critical role in improving feed efficiency, growth rate, and carcass yield. Systems modeling scenarios in which growth-promoting technology was removed from U.S. beef production, considering grazing and confined sectors, predicted substantial declines in productivity, increased resource use, greater manure, and GHG outputs, and higher production costs- with an estimated 8.2 percent effective cost increase for beef (Capper and Hayes, 2012). These observations highlight the link between animal productivity and environmental sustainability that is often underappreciated and unrecognized outside of the beef industry.

Ionophore

Antibiotics can be used to improve cattle health, as well as control and prevent disease, whereas ionophores specifically are typically fed to improve feed efficiency, weight gain per unit of feed consumed (G:F) by altering microbial populations in the rumen and increasing the concentration of propionate relative to acetate, which may decrease hydrogen available for CH_4 production (Goodrich et al., 1984; Stackhouse et al., 2012). Ionophores approved for use in beef cattle are primarily utilized in confined beef production systems. Monensin is a carboxylic polyether ionophore provided to cattle orally as a sodium salt (Haney and Hoehn, 1967). Monensin selectively inhibits Gram-positive bacteria, which impacts ruminant metabolism by increasing efficiency of energy metabolism, improving N metabolism, and reducing bloat and lactic acidosis risk (Schelling, 1984). Monensin changes the ratio of volatile fatty acids in the rumen by increasing propionic acid production and reducing molar percentages of butyric and acetic acids (Richardson et al., 1976; Prange et al., 1978), thus providing more energy from feed to the animal through increased glucose supply (Duffield et al., 2012). Therefore, monensin is often seen to improve feed efficiency and reduce dry matter intake (Duffield et al., 2012). Goodrich et al. (1984) reported an increase in average daily gain (ADG) of 1.6 percent and feed conversion of 7.5 percent, while decreasing dry matter intake (DMI) by 6.5 percent for feedlot cattle fed monensin at 31.8 mg/kg DM. Other carboxylic polyether ionophores that have been approved for use in beef cattle include lasalocid and laidlomycin propionate (Swenson et al., 2025).

Anabolic Implants

Growth promoting anabolic steroidal implants have been used in U.S. beef production since 1956 (Smith and Johnson, 2020). Commercially available implants used in the U.S. beef industry can be comprised of naturally occurring estradiol, synthetically modified estradiol,

estradiol benzoate, or estrogen-like compounds (i.e., zeranol; Smith and Johnson, 2020). These compounds are utilized either alone or in combination with progesterone, testosterone propionate, or trenbolone acetate in differing amounts and ratios of active compounds (Smith and Johnson, 2020). Anabolic implants employ estrogenic (estradiol or zeranol) and androgenic (testosterone or trenbolone acetate) components that work in conjunction with naturally circulating hormones to stimulate feed intake, nitrogen utilization, and protein deposition, increasing cattle growth performance and feed efficiency (Bryant et al., 2010; Drouillard, 2018). Anabolic implants have been reported to have an additive anabolic effect in steers (Heitzman et al., 1977). The anabolic effect of implants has been demonstrated to increase weight gain, by increasing the efficiency and conversion of gain, which is generally accompanied by an increase in DMI (Lee et al., 1990; Mader, 1994). Duckett and Andrae (2001) reported up to 20% greater ADG, 13.5% improvement in feed conversion, and 7.5% increase in hot carcass weight (HCW) depending on implant type and strategy in feedlot steers. In addition to use in confined beef production systems, anabolic implants have been widely adopted for use in stocker cattle in grazing-based production systems (Beck et al., 2022). Duckett and Andre (2001) reported typical improvements of 15% in ADG for implanted stocker cattle when compared to cattle that are not managed with an anabolic implant.

Beta-adrenergic ligands

The importance of growth-promoting technologies in confined beef production systems that increase cattle efficiency, such as beta-adrenergic ligands (β-ligands), to meet the demands of the growing global population cannot be overstated (Bryant et al., 2020; Dilger et al., 2021). Beta-adrenergic ligands comprise a class of growth-promoting compounds that interact with β-adrenergic receptors (β-AR), which are G protein-coupled receptors distributed across a wide range of mammalian tissues (Mersmann, 1998; Dilger et al., 2021). These receptors exist as three primary subtypes (i.e., β_1, β_2, and β_3), with β_2-AR predominating in bovine skeletal muscle and adipose tissue (> 99% and > 90%, respectively), thereby serving as the principal targets for growth-promoting β-ligands utilized in confined beef cattle production systems (Mills et al., 2003; Kim and Hergenreder, 2026). Upon ligand binding, β-AR activation initiates intracellular signaling cascades that increase cyclic AMP, ultimately enhancing protein synthesis, stimulating lipolysis, and reducing lipogenesis (Mersmann, 1998; Dunshea et al., 2005; Kootstra et al., 2005; Bryant et al., 2010; Johnson, 2014; Bryant et al., 2020; Ross et al., 2021). Collectively, these processes repartition nutrients away from adipose deposition and toward lean tissue accretion, improving feed efficiency and carcass yield (Mersmann, 1998; Neumeier and Mitloehner, 2013; Bryant et al., 2020). The magnitude of response is influenced by factors such as receptor subtype specificity, ligand affinity, duration of administration, and animal-related variables including age, weight, diet, and genetic background (Moody et al., 2000; Trojan and Hergenreder, 2026). Consequently, β-adrenergic agonists (β-AA) and modulators are typically administered during the finishing phase of beef production to optimize growth performance and carcass composition as cattle approach physiological maturity. Historically, 4 predominant β-adrenergic ligands have been investigated for use in beef cattle; however, only 2 (*i.e.*, ractopamine hydrochloride and lubabegron) are currently approved by the U.S. FDA and utilized in U.S. confined beef production systems. The primary mode of action and subsequent efficacy of these β-ligands is influenced heavily by the target β-AR the growth-promoting compound interacts with.

Clenbuterol, a potent β_2-adrenergic agonist, was among the earliest compounds investigated for its anabolic effects in livestock. Research conducted in the 1980s demonstrated that oral administration of clenbuterol increased skeletal muscle mass while reducing fat deposition, in some cases also improving ADG and feed efficiency (Mersmann, 1998). For example, administration to young steers for 50 d resulted in a 28% increase in longissimus muscle area without significant changes in adipose fat deposition, suggesting pronounced stimulation of protein accretion during early growth phases (Schiavetta et al., 1990). Despite its efficacy, clenbuterol is not FDA approved for use in beef cattle in the U.S. and many other countries due to concerns regarding human food safety. Its high oral potency and persistence have been linked to cases of acute toxicity in consumers, leading to strict regulatory controls and continued global scrutiny over its illicit use (Smith, 1998; Dilger et al., 2021).

Ractopamine hydrochloride is a β_1-adrenergic agonist approved for use in U.S. beef production in 2003 and is commonly administered during the final 28 to 42 d of the finishing phase (Dilger et al., 2021; Kim and Hergenreder, 2026). Although it preferentially binds β_1-AR, evidence suggests it may also weakly interact with β_2-AR through receptor upregulation (Sissom et al., 2007; Winterholler et al., 2007). Compared with β_2-selective agonists, ractopamine hydrochloride elicits more moderate performance responses, likely due to the lesser abundance of β_1-AR in bovine muscle and adipose tissue. Nonetheless, numerous studies have demonstrated improvements in growth performance and carcass composition when feeding ractopamine hydrochloride to finishing beef steers (Scramlin et al., 2010; Bittner et al., 2015; Genther-Shroeder et al., 2016; Bryant et al., 2010; Bryant et al., 2020; Hales et al., 2016). Cattle fed ractopamine hydrochloride generally have greater ADG, yield heavier HCW, grade with a smaller numerical yield grade, and have a larger longissimus muscle area, when compared to cattle not fed ractopamine hydrochloride. However, ractopamine hydrochloride also decreases intramuscular fat deposition, resulting in lesser marbling scores, but detrimental effects on USDA quality grade have not been observed. (Johnson, 2004; Gruber et al., 2007; Winterholler et al., 2007; Bryant et al., 2020; Hales et al., 2016). In a meta-analysis of 32 studies with feedlot steers fed ractopamine hydrochloride at

100 mg/d, 200 mg/d, and 300 mg/d, Pyatt et al. (2013) reported that live weight gain increased by 3.4, 6.8, and 10.2 kg while HCW increased by 3.1, 6.1, and 9.2 kg, respectively. Lean et al. (2014) conducted a meta-analysis investigating growth performance characteristics of feedlot cattle supplemented with ractopamine hydrochloride and reported supplementation resulted in approximately an 8 kg increase in BW and 0.19 kg/d increase in ADG with no substantial difference in DMI compared to non-supplemented cattle. Mechanistically, these outcomes are driven by enhanced protein synthesis and reduced protein degradation, alongside increased lipolysis and decreased lipogenesis (Mersmann, 1998; Dunshea et al., 2005). In addition to its efficacy, ractopamine hydrochloride does not require a withdrawal period prior to slaughter, which has further contributed to its widespread adoption in confined beef finishing systems.

Zilpaterol hydrochloride is a β_2-adrenergic agonist characterized by a high affinity for β_2-AR, the predominant receptor subtype in bovine skeletal muscle (Kim and Hergenreder, 2026). Approved for use by the U.S. FDA in finishing cattle in 2006 for 20 to 40 d prior to harvest, zilpaterol hydrochloride has consistently demonstrated greater growth-promoting effects than ractopamine hydrochloride, including significant increases in ADG, feed efficiency, dressing percentage, and carcass leanness (Dilger et al., 2021). When fed zilpaterol hydrochloride, dressing percent of cattle generally increases approximately 1.5 to 2.0 percent when compared to cattle not fed zilpaterol hydrochloride (Dilger et al., 2021). The mode of action of zilpaterol hydrochloride mirrors that of other β-AA, but the preferential targeting of β_2-AR amplifies anabolic signaling in muscle tissue, resulting in pronounced increases in protein accretion and reductions in fat deposition. However, zilpaterol hydrochloride requires a mandatory 3 d withdrawal period in the U.S. prior to harvest and has been associated with animal welfare concerns, particularly related to mobility and musculoskeletal impacts. These concerns led to the voluntary suspension of its use in the U.S. in 2013, although it remains approved in some countries (Kim and Hergenreder, 2026).

Lubabegron represents a novel class of β-ligands classified as a selective β-adrenergic receptor modulator (SβM), exhibiting agonistic activity at β_3-AR while antagonizing β_1- and β_2-AR (Dilger et al., 2021; Trojan and Hergenreder, 2026). This distinct receptor profile differentiates lubabegron from traditional β-AA, as β_3-AR are less abundant in skeletal muscle and adipose tissue and are instead associated with systemic metabolic regulation. Consequently, the effects of lubabegron are mediated through indirect metabolic pathways, including enhanced glucose utilization and improved nitrogen retention, rather than direct stimulation of muscle protein synthesis (Trojan and Hergenreder, 2026). Approved by the U.S. FDA in 2018, lubabegron is uniquely labeled for reducing ammonia emissions per unit of live or CW, reflecting its role in improving environmental sustainability rather than solely enhancing growth performance (Dilger et al., 2021). When feeding lubabegron at 5 g/ton, ammonia emissions per pound HCW were reduced 16%, a combination of an absolute reduction in ammonia by approximately 12% and an increase in CW of approximately 5% (Dilger et al., 2021). The feeding duration of lubabegron ranges from 14 to 91 d, and its reduced susceptibility to receptor desensitization provides greater flexibility in management compared with traditional β-AA. Collectively, lubabegron highlights the innovation and evolving role of β-ligands in balancing production efficiency with environmental stewardship in beef systems.

Implications for sustainability regarding growth-promoting technology

Regardless of the specific growth-promoting technology utilized, a consistent theme emerges- improvements in animal growth rate and feed efficiency translates directly into reductions in land, water, feed, nutrient excretion, and GHG emissions per unit of beef. Growth-promoting technologies that enhance rumen fermentation efficiency, nutrient utilization, and muscle deposition reduce the biological and environmental overhead required to produce beef. Ultimately, the integration of confined beef finishing systems with the use of growth-promoting technologies can represent an economically efficient production strategy under prevailing market conditions and regulatory frameworks, while also contributing to improved environmental efficiency in modern beef production systems. However, these outcomes are context-specific and may vary with shifts in market dynamics, consumer preferences, and policy/regulatory conditions.

Climate change poses risk to beef cattle efficiency

The growth performance, health, and wellbeing of cattle is strongly influenced by climatic conditions. Regardless of sector (*i.e.*, cow-calf, stocker/backgrounder, and feedlot), beef production systems generally manage cattle outdoors where cattle are exposed to natural and variable environmental conditions. Cattle are particularly vulnerable not only to extreme environmental conditions, but also to rapid changes in these conditions (Mader, 2003). Additionally, the duration of climatic conditions is also an important factor in assessing an animal's ability to cope with environmental stress. Events lasting one day in duration are likely to occur frequently and have small impacts on animal productivity, but events lasting multiple days have the potential to result in severe animal wellbeing and economic impacts (Hubbard et al., 1999). Heat waves and/or periods of severe winter weather have the ability to result in significant losses to beef production systems in the U.S., posing a threat to the economic prosperity of the beef industry (Mader, 2003).

Discomfort experienced by these adverse climatic conditions may result in reduced DMI, reduced BW gain, and potential cattle deaths (Hahn, 1994; Lefcourt and Adams, 1996; Mader et al., 1997b). Altering the microclimate where cattle are raised by providing protection from climatic conditions is one of the most useful husbandry interventions that can be implemented to help animals cope with heat and cold stress conditions (Mader, 2003; Mader et al., 1997a,b; 1999). Management alternatives such as facility modifications, dietary manipulation, environmental adaptation, and cattle selection may be beneficial for cattle challenged by heat and cold stress conditions.

Adaptive management strategies for a changing climate in confined beef production systems

<u>Facility Modifications</u>

Adaptive management of cattle in confined beef production systems during extreme weather events must prioritize alleviating the burden of environmental stress over maintaining animal performance during adverse events (Mader and Griffin, 2015). Facility alterations allow for adaptive management of cattle in confined settings throughout different seasons (Mader, 2003; Mader and Griffin, 2015). In cold months, the use of wind protection and bedding has been shown to improve cattle gain and efficiency of gain (Birkelo and Lounsbery, 1992; Stanton and Schultz, 1996; Mader, 2003). In summer months, sprinklers and shade have been observed to help cattle cope with extreme heat and improve performance (Mader, 2003; Mader and Davis, 2004; Morrison et al., 1973; Morrison et al., 1981; Igono et al., 1985; Armstrong, 1994; Lin et al., 1998; Chen et al., 1993).

In regard to the use of shade in summer months when ambient temperatures are elevated, Mader (2003) observed that the physiological response cattle have to shade is generally manifested within the initial 56 days on feed, despite shade utilization generally increasing the longer cattle are on feed. This suggests that cattle must adapt to shade or the social order around and under shade in a pen before optimal shade use occurs (Mader, 2003). The implementation of shade in confined beef production systems does not resolve all incidences of heat stress in feedlots since heat stress is dependent not only on temperature and solar radiation, but also on humidity and wind speed (Mader, 2003). Moreover, facility management strategies need to be adaptable to the seasonal differences since wind protection near cattle in the summer can have adverse animal wellbeing impacts due to the role that ventilation and wind speed contribute to the ability for cattle to regulate body temperature during hyperthermia events (Mader, 2003).

There are other animal husbandry factors, such as pen density, that are important in ensuring adequate access to feed, water, and protective barriers (i.e., shade and windbreaks) during adverse climatic conditions (Mader, 2003). Furthermore, the overall economic benefit of facility modification depends not only on location, but also on the cost of modifications and maintenance. Economics could serve as a potential challenge for the implementation of facility modification strategies. Nonetheless, rational, cost-effective facility modification strategies may be needed to reduce climate-related cattle losses in feedlots (Mader, 2003). Future research should provide an updated assessment quantifying the economic impacts of heat and cold stress which could provide incentives for industry adoption of facility modification strategies.

Dietary Manipulation

In addition to facility modifications, dietary manipulation in confined beef production systems may be beneficial for cattle challenged by adverse climatic conditions (Mader, 2003). Problems in managing cattle exposed to elevated climatic temperatures may be further complicated if cattle are being fed high-energy diets (Brosh et al., 1994; Reinhardt and Brandt, 1994; Gaughan et al., 1996; Mader et al., 2002), which contributes to elevated metabolic heat load (Mader, 2003). Reducing maintenance energy intake through modified feed management could decrease heat production and enhance feed conversion (Purwanto et al., 1990; Hicks et al., 1990; Murphy et al., 1994; Murphy and Loerch, 1994). However, seasonality will influence adaptive management strategies for dietary manipulation. A need exists for greater maintenance energy intake in the winter to minimize impacts resulting from cold stress, whereas in a hot environment, animals must dissipate metabolic heat when there is a reduced thermal gradient between the internal and external environment (Mader, 2003).

Furthermore, altering feeding time and/or the amount of feed fed has been demonstrated to be beneficial in reducing heat stress (Brosh et al., 1998). Feeding cattle in a manner that prevents the occurrence of peak metabolic heat load at the same time as peak environmental heat load is an additional dietary manipulation strategy (Reinhardt and Brandt, 1994; Brosh et al., 1998). Moreover, higher-producing animals, which consume more feed and consequently more metabolic heat, have been observed to be more susceptible to heat stress (Mader, 2003). Feeding programs, either when used by themselves or in combination with facility modifications, may better aid in stress alleviation and provide a more comfortable environment for cattle.

Adaptation to Environment

Adapting cattle to their environment has been shown to improve resiliency to changes in climatic conditions when cattle are managed in confined beef production systems (Young, 1985; Mader et al., 2002). Adaptation, within this context and consistent with Young (1985) and Mader et al. (2002), can be defined as a reduction in the severity of physiological and/or behavioral responses to environmental stressors and enhanced capacity of cattle to cope with and overcome environmental-related challenges. The concept of adaptation was demonstrated when cattle adapted to temperatures in the upper or lesser region of the thermoneutral zone were not stressed when exposed to abrupt changes in temperature outside the thermoneutral zone which normally would trigger heat or cold stress in cattle that did not undergo an adaptation period (Young, 1985). Additional research has reported that facility and management modifications do not need to eliminate environmental stress completely for feedlot beef cattle, but rather minimize the severity of the climatic conditions to aid cattle in coping with the stressor (Mader et al., 2002).

Cattle Breed Selection

As environmental temperatures increase, understanding biological determinants of heat tolerance, such as coat color and breed type, becomes increasingly important for beef production systems. Cattle with dark hair coats have been observed to have greater tympanic temperature when compared to cattle with light hair coats (Mader et al., 2002). Additionally, observations have reported that in commercial feedlots, black-haired steers have exhibited body surface temperatures as much as 21°C greater when compared to white-haired contemporaries (Arp et al., 1983). Cattle breed selection decisions could also consider the use of more heat tolerant breeds of cattle originating from tropical environments. Future research should consider the use of *Bos indicus* or *Bos indicus* × *Bos taurus* crossbred cattle in warmer production environments. To date, comparatively limited research has evaluated the adaptability and performance of these genotypes under more temperate climatic conditions.

Current research investigating Bos indicus and Bos taurus cattle in beef production systems

As extreme weather events become more common and threaten the prosperity of the beef industry, beef cattle producers may consider increasing the proportion or percentage of *Bos indicus* species of cattle in their operations, which are known for their heat tolerance compared to *Bos taurus* breeds of cattle (Beatty et al., 2006). In the U.S., *Bos indicus* cattle were first introduced to the Gulf Coast region to improve adaptability of beef cattle to the subtropical environmental conditions (Cartwright, 1980; Huffman et al., 1990). The greatest advantage of *Bos indicus* cattle in the U.S. has been realized in crossbreeding programs, where heterosis contributes to improved production characteristics while enhancing tolerance to heat, disease, and parasites, particularly in the southern and southeastern U.S. where cattle are exposed to hot, humid climates and poor-quality forages (Paschal et al., 1995). Most *Bos indicus* cattle in the U.S. were imported from Brazil, although their ancestral origin is India, in contrast to *Bos taurus* cattle which are of European origin (Sanders, 1980). Morphological traits that distinguish *Bos indicus* from *Bos taurus* cattle include the cervico-thoracic hump, large pendulous ears, and excessive skin along the ventral body surface, chest, and neck (Utsunomiya et al., 2019). Beyond physical characteristics, *Bos indicus* and *Bos taurus* cattle differ in several important biological and production characteristics, including (1) heat and cold tolerance, (2) reproduction, (3) growth and maturation rates, (4) temperament, and (5) complementarity in crossbreeding systems (Cartwright, 1980).

Bos indicus cattle have been observed to have lesser maintenance requirements than *Bos taurus* cattle (van der Merwe and van Rooyen, 1980; Frisch and Vercoe, 1982; Solis et al., 1988; Carstens et al., 1989; Hotovy et al., 1991). This energetic requirement difference allows *Bos indicus* cattle to perform as well or better in nutritionally restrictive environments when compared to *Bos taurus* cattle (Ferrell and Jenkins, 1998). However, in a better nutritional environment, *Bos indicus* cattle generally consume less feed ad libitum and achieve lesser rates of gain than *Bos taurus* cattle, which may limit their performance and use in the U.S. beef industry (Rogerson et al., 1968; Frisch and Vercoe, 1977). Moreover, in the U.S., beef producers are typically paid on a grid system, resulting in yield and quality grade being pivotal (Schroeder et al, 2009). Previous research has recommended that when steers have at least 50% *Bos indicus* influence, they will be unacceptable to the cattle feeder if quality grade is used to determine price at harvest, due to a decrease in marbling score- generally corresponding to the USDA Select quality grade, when compared to *Bos taurus* cattle (Boyles, 1985). As a result of these differences, economic (*i.e.*, growth performance and carcass quality) and social concerns (*i.e.*, consumer acceptance of meat quality, and cattle temperament) have been documented for BI cattle (Boyles and Riley, 1991; Voisinet et al., 1997; Wright et al., 2018).

Brahman is the only *Bos indicus* breed maintained in significant numbers in the U.S. (Cartwright, 1980). Few studies have investigated the performance of *Bos indicus* (Brahman) and *Bos taurus* (Angus) cattle. When comparing the two breeds, observations have reported that Angus steers have greater DMI when compared to Brahman influenced steers (Boyles and Riley, 1991; Ferrell and Jenkins, 1998). It has also been postulated that Angus cattle have a larger digestive tract by weight than Brahman cattle, which may explain the difference in intake (Butler et al., 1956; Carpenter et al., 1961; Boyles and Riley, 1991). Growth has been observed to increase more rapidly for Angus steers than for Brahman influenced steers (Boyles and Riley, 1991). Angus steers have demonstrated greater ADG, requiring fewer days on feed when finished to a common compositional or weight endpoint, when compared to Brahman steers (Boyles and Riley, 1991; Adams et al., 1982).

When assessing carcass characteristics, Angus cattle have been reported to yield heavier HCW when compared to Brahman influenced cattle (Ferrell and Jenkins, 1998). Boyles (1991) reported that when comparing steers of similar age and final body weight (FBW; approximately 507 kg) harvested at 184 d on feed, Brahman-Angus steers had 0.5 cm less subcutaneous backfat at the 12^{th} rib. Moreover, Boyles and Riley (1991) reported that the longissimus muscle area (LMA) between the 12^{th} and 13^{th} rib of Angus steers was approximately 5 cm^2 less than BI steers. There has been reported variability regarding yield grade difference between Angus and Brahman steers. Some studies show no difference in yield grade (Ferrell and Jenkins, 1998) and others have reported Angus cattle possess greater numeric yield grades, more fat at the 12th rib, when compared to Brahman cattle (Boyles and Riley, 1991). Moreover, Angus steers generally have higher marbling scores contributing to higher quality grades (Boyles and Riley, 1991; Ferrell and Jenkins, 1998). Boyles and Riley (1991) reported that 90 percent of Angus steers graded U.S. Department of Agriculture (USDA) Choice, while only 10 percent of the Brahman influenced steers graded USDA Choice. The notable quality grade difference between Angus and Brahman cattle could be problematic in a demand-driven industry, such as the U.S. beef industry that dictates superior quality and consistency (Damon et al., 1960; Young et al., 1978; Koch et al. 1982; Boyles and Riley, 1991).

Not only are feedlot and carcass performance important considerations for the incorporation of *Bos indicus* cattle into the U.S. beef industry, but temperament may also be a consideration for multiple reasons. More docile animals may be preferred due to concerns of handler safety and decreased facility wear (Voisinet et al., 1997). A reduction in animal stress and incidence of animal injury that could impact performance may also incentivize selection of calmer cattle breeds (Voisinet et al., 1997). Temperament is not only an important cattle selection factor from a handler and animal welfare aspect, but also from an economic standpoint, which often goes without recognition (Voisinet et al., 1997). In a study conducted by Voisinet et al. (1997), temperament scores were evaluated for Brahman (*i.e.*, *Bos indicus*) and British (*i.e.*, *Bos taurus*) cattle groups, and demonstrated that increased temperament score resulted in decreased ADG. Moreover, research has shown that *Bos indicus* cattle are more temperamental, or excitable, than *Bos taurus* cattle (Elder et al., 1980; Hearnshaw and Morris, 1984; Fordyce et al., 1988; Voisinet et al., 1997). Temperament has been reported to be associated with behavioral reactivity in cattle, including agitation and excitability during handling or restraint (Grandin, 1994; Voisinet et al., 1997). Cattle classified as more excitable have demonstrated to exhibit greater stress responses during handling, which may result in increased risk of injury and reduced ADG (Grandin, 1994; Voisinet et al., 1997). Therefore, temperament represents an important consideration in cattle selection decisions, as highly excitable cattle may pose challenges to long-term social and economic sustainability within U.S. beef production systems (Grandin, 1994; Voisinet et al., 1997).

Ultimately, there are challenges associated with incorporating Brahman cattle into the U.S. beef industry. Preceding research has observed drawbacks to increasing the proportion of *Bos indicus* genetics in the fed cattle industry, which are: 1) decreased growth performance (Adams et al., 1982; Boyles and Riley, 1991) and 2) poorer carcass attributes (Boyles and Riley, 1991; Ferrell and Jenkins, 1998) relative to *Bos taurus*. These drawbacks warrant the need for cattle managers feeding Brahman influenced cattle to pay greater attention to the price differential between USDA Choice and USDA Select quality grades when making grid-based marketing decisions that consider yield and quality grade (Boyles and Riley, 1991). Additionally, Brahman cattle have predominantly been evaluated under hot climatic conditions; however, ongoing climatic variability includes not only rising temperatures but also the occurrence of extreme cold events. Limited research conducted in temperate environments has quantified performance differences and survivability of Brahman cattle under such conditions. Consequently, further investigation is warranted to compare the productivity and adaptability of Brahman and Angus cattle in temperate regions where Angus genetics traditionally predominate, thereby enabling assessment of potential production tradeoffs. Moreover, although growth-promoting technologies have been associated with improvements in productivity and efficiency, previous research indicates that breed-specific responses to growth-promoting technologies may differ (Reichhardt et al., 2023). Quantifying these differential responses is essential to inform cattle breed selection and management strategies aimed at enhancing the resilience of beef production systems under variable environmental conditions.

CONCLUSION

As pressure associated with growing concern of anthropogenic greenhouse gas emissions, population growth, and resource constraints increases, the U.S. beef industry will be required to improve productivity while reducing environmental impacts across one of the most complex and multi-faceted supply chains. Addressing these challenges requires prioritization of improved 1) quantification of GHG emissions associated with beef cattle production, 2) evaluation of growth-promoting technologies within production systems, and 3) development of scalable strategies to adaptively manage and select cattle under increasingly variable climatic conditions. As the climate changes, more extreme weather events and variable precipitation are anticipated to increase in severity and frequency which may challenge the resiliency and adaptive capacity of U.S. beef production systems. As extreme weather events become more common and threaten the prosperity of the industry, feedlot production systems may consider increasing the proportion or percentage of *Bos indicus* sub-species of cattle in their operations, which are known for their heat tolerance. In response, feedlot production systems may consider incorporating a greater proportion of *Bos indicus* genetics due to their enhanced heat tolerance; however, further research is needed to evaluate their performance across diverse production environments and to assess potential tradeoffs, including possible production limitations under colder or more temperate climatic conditions.

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Table 1.1. Reported Carbon Footprints of Beef Production from Selected Life Cycle Assessments

Publication	Functional Unit[1]	Carbon Footprint[2]
Stackhouse-Lawson et al., 2012	kg CW	10.7-22.6
Heflin et al., 2019	kg CW	9.6-27.5
Rotz et al., 2019	kg CW	17-40 (avg. 23.3)
Putman et al., 2023	kg CW (partial LCA)	21
Vergé et al., 2008	kg BW	10
Rotz et al., 2013	kg BW	10.9
Heflin et al., 2019	kg gain	4.8-26.5
Asem-Hiablie et al., 2019	1 kg of consumed, boneless edible beef	7.42
Putman et al., 2023	kg consumed beef (full LCA)	42.7
Werth et al., 2021	kg TMR	0.521-0.630

[1]CW= carcass weight, BW= body weight, TMR= total mixed ration
[2]Carbon footprint in kg CO_2 equivalents

CHAPTER 2- EVALUATION OF CATTLE SUB-SPECIES AND GROWTH-PROMOTING TECHNOLOGY ON GROWTH PERFORMANCE, CARCASS CHARACTERISTICS, AND GAS FLUX OF STEERS FINISHED IN SUMMER FEEDLOT CONDITIONS[1]

INTRODUCTION

Sustainability is a dynamic state of continuous improvement that encapsulates balancing economic, social, and environmental factors in a constantly evolving ecosystem. As atmospheric concentrations of greenhouse gases (GHG) continue to increase at an unprecedented rate, resulting in increasingly severe, interconnected, and often irreversible climate impacts, a shift of perspective to mitigation in tandem with adaptation is required (Pörtner et al., 2022). When considering the agriculture industry, GHG are emitted from agricultural activities through a variety of processes, such as enteric methane (CH_4) production from ruminant livestock. In the United States (US), enteric CH_4 emissions from beef cattle comprise approximately 2 percent of total US GHG emissions (EPA, 2024). Beef cattle production in the US expands across a range of climatic zones from subtropical to temperate, and the threat of increased thermal load of finishing beef cattle is a sustainability challenge. Methodologies that have been proposed for feedlot beef cattle to address risks posed by a warming climate include 1) utilization of growth-promoting technologies (GPT) (Reichhardt et al., 2023), 2) increasing the proportion of *Bos indicus* (BI) breeds that are more adapted to hot and humid climates (Boyles and Riley, 1991; Ferrell and Jenkins, 1998; Elzo et al.,

[1] Schilling-Hazlett, A.K., K.R. Stackhouse-Lawson, T.C. Bryant, J.J. Vargas, S.E. Place, J.P. Ritten, E.C. Martins, W.A. Souza, M.A. Swenson, E.N. Burke, R.K. Campion, A.M. Shadbolt, and P.H.V. Carvalho. 2025. Evaluation of cattle sub-species and growth-promoting technology on growth performance, carcass characteristics, and gas flux of steers finished in summer feedlot conditions, J. Anim. Sci. 103. doi:10.1093/jas/skaf322.

2009), and 3) modification of facilities and feed management practices (Reinhardt and Brandt, 1994; Mader, 2003; Mader and Davis, 2004).

The use of GPT is suggested to be one of the most effective mitigation strategies to decrease GHG emissions from beef production per unit of feed consumed and product produced (Boadi et al., 2004; Monteny et al., 2006; Stackhouse et al., 2012).The main GPT used in finishing operations are antibiotics, ionophores, anabolic implants, and beta-adrenergic ligands (Stackhouse-Lawson et al., 2013). Antibiotics can be used to improve cattle health, as well as control and prevent disease, whereas ionophores are typically fed to improve feed efficiency (Goodrich et al., 1984; Stackhouse et al., 2012). Anabolic implants employ estrogenic (estradiol or zeranol) and androgenic (testosterone or trenbolone acetate) components to improve feed intake, nitrogen utilization, and protein deposition (Bryant et al., 2010; Drouillard, 2018). Moreover, ractopamine hydrochloride, a beta-adrenergic agonist, can be fed to feedlot cattle during the last 28 to 42 d of the feeding period to reduce ammonia emissions, promote protein deposition and improve G:F, leading to increased HCW (Mersmann, 1998; Bryant et al., 2010; Johnson, 2014). Despite potential productivity and efficiency improvements resulting from the use of GPT, previous research has reported that different cattle breeds may respond differently to GPT (Reichhardt et al., 2023). Therefore, it is important to quantify differences in the effect of GPT to best inform future breed selection and management decisions to ensure the resiliency of beef production systems.

Breed comparison research, observing primarily growth performance and carcass attributes of *Bos taurus* (BT) and BI sub-species of cattle were explored extensively throughout the 20th century as cattle producers were importing BI cattle to the US (Black et al., 1934; Sanders, 1980; Paschal et al., 1995). Nearly half a century since the foundational and preliminary comparisons of BI and BT cattle, an eminent need exists to proactively address the climate adaptivity and resiliency of beef cattle in a rapidly changing climate. However, preceding research has observed 3 primary drawbacks to increasing the proportion of BI genetics in the fed cattle industry, which are: 1) decreased growth performance (Adams et al., 1982; Boyles and Riley, 1991), 2) poorer carcass attributes (Boyles and Riley, 1991; Ferrell and Jenkins, 1998) and 3) more excitable cattle temperament (Voisinet et al., 1997), relative to BT. Moreover, despite their global prominence, BI cattle are underrepresented in current CH_4 emissions evaluations from ruminant species (Della Rosa et al., 2022). With limited data available representative of current cattle type and technology comparing the growth performance, carcass characteristics, and gas flux, a need exists for comparative feedlot research of BI and BT steers to aid in future beef industry sustainability assessments.

Therefore, the objective of the current experiment was to evaluate enteric gas flux of CH_4, CO_2, O_2, and H_2, growth performance, and carcass characteristics of BI and BT sub-species managed with and without the use of GPT in summer conditions. The authors hypothesized that BT steers and steers managed with GPT would exhibit greater growth performance, primarily due to greater feed intake and feed efficiency compared to BI steers and steers not managed with GPT. Predicted difference in growth performance will influence enteric gas flux emissions, where cattle that consume more feed are expected to exhibit greater CH_4 emissions; thus, BT steers are expected to have greater CH_4 emissions than BI steers.

MATERIALS AND METHODS

This experiment was conducted at the Colorado State University Agricultural Research, Education, and Development Center experiment station in Fort Collins, Colorado, from April to October 2023, consisting of one continuous 180 d feeding period divided into 2 phases. All procedures involving animals were approved by the Colorado State University Institutional

Animal Care and Use Committee (protocol no. 3712). All animals evaluated in the current study were sourced in two lots by Five Rivers Cattle Feeding, where lot 1 was comprised of BT steers sourced from Montana and lot 2 of BI steers sourced from Texas. Steers of BI origin were allotted 10 d to acclimate to the research facility prior to study initiation; whereas BT steers were allotted 4 d. Acclimatization was determined based on differences in climatic conditions between the research facility and source location for each lot.

Animals and Experimental Design

Animals consisted of 100 BI (Brahman) yearling steers (initial body weight (IBW) = 342 kg ± 31 kg) and 100 BT (Angus) yearling steers (IBW) = 341 kg ± 21 kg). Steers of each sub-species were randomly assigned to a management treatment, managed with the use of GPT (TRT) or without the use of GPT (CON), in a 2×2 factorial arrangement of treatments. Steers in TRT received an in-ear anabolic implant on d 0 (100 mg trenbolone acetate/14 mg estradiol benzoate; Synovex Choice, Zoetis, Parsippany, NJ, USA) and d 84 (200 mg trenbolone acetate/28 mg estradiol benzoate; Synovex Plus, Zoetis). Steers in TRT also received an in-feed ionophore (35 g/ton DM basis; monensin, Rumensin, Elanco, Greenfield, IN, USA) and antibiotic (7 g/ton DM basis; tylosin, Tylan, Elanco) from d 0-180. Also, TRT steers received a beta-adrenergic agonist during the last 42 d of the feeding period (27 g/ton DM basis; ractopamine hydrochloride, Actogain, Zoetis), allowing for a 2 d withdrawal period prior to harvest. The CON steers did not receive any of the above-listed GPT.

Regardless of management and sub-species, all cattle were vaccinated with 2 mL Bovi-Shield GOLD 5 (Bovine rhinotracheitis-virus diarrhea-parainfluenza 3-respiratory syncytial virus vaccine, Zoetis), 2 mL Ultrachoice 8 (clostridial vaccine, Zoetis), Dectomax (doramectin, Zoetis), and orally drenched with Valbazen (albendazole, Zoetis) within 48 h period post arrival to the feedlot. All cattle received a radio frequency identification tag (Allflex, USA Inc., Dallas, TX, USA) placed in the left ear of each animal on the same processing date.

Steers were fed for 180 d in 2 consecutive phases. In Phase 1 (d 0 to 83), steers were housed for 84 d in research pens (7 m×40 m), where cattle were blocked by weight and randomly assigned to a pen, where the pen was considered the experimental unit (10 steers/pen; 5 pens/treatment). Each pen was equipped with a concrete feed bunk (30 cm/animal), a 3 m × 7 m concrete bunk pad, and an automatic water tank (model no. C250, Cancrete Cattle Waterer, Advanced Agri-Direct Inc. York, NE, USA). In Phase 2 (d 84 to 180), cattle were moved to 1 of the 4 Climate Smart Research Pens (15 m × 43 m) for the remaining 96 d of the experimental period. Each Climate Smart Research Pen housed 50 steers/pen, equipped with 1 GreenFeed automated head chamber system (AHCS, C-Lock, Rapid City, SD, USA), 5 SmartFeed (SF, C-Lock, Rapid City, SD, USA) bunk systems, 2 automatic water tanks, a concrete bunk pad (15 m × 3 m), and a metal roof (15 m × 3 m) covering the SFs, AHCS, and approximately 7% of the pen surface. Treatments were randomly assigned to a Climate Smart Research Pen (1 pen/treatment), and the experimental unit was considered the individual animal (50 steers/treatment).

Throughout the experimental period, steers were monitored daily by trained personnel who evaluated fresh feed and water allocation, cattle health, locomotion, and clinical signs of disease. Steers exhibiting signs of respiratory disease were removed from the pen to assess rectal body temperature and body weight (BW). Cattle with body temperatures greater than 39.4°C were classified as clinically ill. All clinically ill steers were treated according to the appropriate treatment protocol prescribed by a licensed veterinarian and immediately returned to their pen of origin. Cattle that were managed under the CON strategy that were treated were documented and not included in the analysis of data in order to simulate a production typical scenario representative of a "natural" labeled beef program where cattle treated with antibiotics are removed from the production system. Following the completion of the experimental period, a total of 6 steers were removed from data analysis due to injury or illness: 1 BI TRT, 1 BI CON, and 4 BT CON.

Feed Management and Intake

All steers were transitioned to the final finishing diet after a 21 d adaptation from a starter diet to a finishing diet, including two intermediate step-up diets (Table 1). Feed samples were collected weekly, dried at 65 °C for a minimum of 48 h to determine dry matter (DM), and ground to pass through a 2 mm screen (Wiley Mill, Model 4; Arthur H. Thomas Co., Philadelphia, PA, USA) and preserved at room temperature. After the completion of the experimental period, feed samples were composited and analyzed at a commercial laboratory using a wet chemistry package (Ration Balancer Plus with Gross Energy and Starch, Dairy One, Ithaca, NY, USA). Acid detergent fiber analysis was conducted following ANKOM Technology Method 12, where 0.5 g of a feed sample was individually weighed, placed in a filter bag, and digested in an ANKOM DELTA Digestion Unit for 75 minutes in 2 L of acid detergent fiber solution. Samples were rinsed three times with boiling water for 5 minutes in filter bags followed by a 3 minute acetone soak and drying at 105 ºC for 2 hours. Neutral detergent fiber analysis was conducted following ANKOM Technology Method 13, where 0.5 g of a feed sample was individually weighed, placed in a filter bag, and digested in an ANKOM DELTA Digestion Unit for 75 minutes in 2 L of neutral detergent fiber solution. At the start of digestion, 4 ml of Alpha Amylase and 20 g sodium sulfite were added. Sample were then rinsed three times with boiling water for 5 minutes, with 4 ml Alpha Amylase added to the first two rinses. Water rinses were followed by a 3 minute acetone soak and drying at 105ºC for 2 hours. Analysis of lignin was determined following ANKOM Technology Method 9 using a DaisyII Incubator. For crude protein analysis, dried feed samples were ground to 1 mm and combusted using a CN628 Carbon/Nitrogen Determinator. Determination of ash used the Association of Official Agricultural Chemists Official Method 942.05- Ash for Animal Feed. Gross energy was determined using bomb calorimetry.

During Phase 1, slick-bunk management was utilized to manage feed delivery to the feed bunk, where feed bunks were evaluated at approximately 0700 hours daily to estimate orts and adjust feed calls to ensure *ad libitum* access to feed. Feed intake data were averaged daily on a steer/pen basis. Daily feed allocation per pen was divided by the number of steers/pen, averaged by week, and multiplied by the percent DM of the total mixed ration to determine average daily dry matter intake (DMI) on a weekly basis. During Phase 2, individual animal feed intake was determined utilizing SF bunk systems, and *ad libitum* bunk management was utilized to manage feed delivery (approximately 2.5% orts). A ratio of approximately 1 feeder per 10 steers was maintained throughout the experimental period. The SF bunks were evaluated at approximately 0700 hours daily where the manufacture's online dashboard was utilized to report orts. Fresh feed was delivered once daily to achieve no less than approximately 5 kg remaining in each feeder the following day at 0700 hours. All cattle underwent a 7 d acclimation period to the SF bunks before the initiation of data collection. Feed intake data collected during the acclimation period were not used in data analysis. The SF bunks were calibrated at the beginning and end of the experimental period and every 7 d during the experimental period. Following the termination of the experimental period, raw feeding events were downloaded from the manufacturer's online software. Feeding events that were flagged by the manufacturer (unallocated feed or nonsensical eating rate) exceeded 3600 s in duration and/or were greater than 10 kg mass difference were omitted from data analysis. Feeding events were summed by day and averaged by week to determine weekly as-fed feed intake. As-fed feed intake was converted to DMI by multiplying by the percent DM of the total mixed ration. To determine the average DMI for each phase, weekly DMI was averaged over the feeding period phase. During Phase 2 of the experimental period, DMI from alfalfa pellet drops from the AHCS was added to the total mixed ration daily intake to determine total daily DMI. In addition to total daily DMI in Phases 1 and 2, DMI as a percentage of BW was calculated for each phase using Equation 1.

Equation 1:

$$DMI, \%\ BW = \frac{Dry\ matter\ intake, kg}{BW, kg} \times 100$$

Growth Performance

Steers were individually weighed using a hydraulic squeeze chute (Model no. SHEW10497, Silencer, Moly Manufacturing Inc., Lorraine, KS, USA) equipped with an electronic weighing system (ID5000, Tru-Test Inc., Mineral Wells, TX, USA) on 2 consecutive days at beginning of the experiment (d −1 and 0) to determine IBW and at the end (d 179 and 180) of the experimental period to define final BW (FBW). In addition to IBW and FBW, steers were weighed every 28 d during the experimental period. Experimental mid-point BW (MBW), collected on d 84, was used as the FBW for Phase 1 and IBW for Phase 2. Weight data collected were reduced by 4% to account for digestive tract fill (i.e., shrunk body weights [SBW]; NASEM, 2016). The SBW from each time point, every 28 d, was used to obtain cattle average daily gain (ADG) by subtracting the SBW of the previous time point from the SBW of the current time point and then dividing by the number of days between the 2 weight collection periods.

Gas Flux

Each Climate Smart Research Pen contained one AHCS for the collection of gas fluxes for CH_4, CO_2, H_2, and O_2. Steers were exposed to the AHCS during an acclimation period of 7 d before the initiation of data collection. The headbox extension panels (*i.e.*, wings) were placed on the AHCS system on d 3 of the acclimation period. On d 5 of the acclimation period, cattle panels were used to create an alley in front of the AHCS to ensure only 1 steer at a time had access to the AHCS. Measurements collected during the acclimation period were not included in the data analysis. Throughout the study, steers were allowed to visit the AHCS system up to 6 visits/d, with a minimum of 4 h between each visit. The AHCS was programmed to allow consumption of up to 6 drops of alfalfa pellets per visit (approximately 38 g as fed/drop), with drops occurring every 30 s while a steer was utilizing the AHCS system. These configuration settings encouraged an even distribution of visits per steer throughout the day, capturing the diurnal variation in gas flux and ensuring a steer remained at the AHCS for a minimum duration of 2 min during gas flux sample collection (Vargas et al., 2024).

To ensure proper functioning and performance of the AHCS, CO_2 recovery tests were performed at the beginning, end, and every 28 d throughout the experimental period to gravimetrically calibrate the AHCS. Additionally, zero and span calibrations of the CH_4, CO_2, H_2, and O_2 gas analyzers were performed every 3 d via an autocalibration system located onboard the AHCS. Raw collection data were validated by the AHCS manufacturer, which included checking head proximity, visit length, and airflow, as well as providing corrections for wind. Data were excluded when the length of the visit was less than 2 min, greater than 8 min, and the airflow was less than 26 L/s (Arthur et al., 2017; Gunter and Beck, 2018). Steers were excluded from the analysis of data if the total number of visits collected throughout Phase 2 was less than 40 (Beck et al., 2024). Of the 194 steers, excluding the 6 steers that were removed from the trial for health-related reasons, 166 steers met the filtering requirements to be included in the analysis of gas flux data analysis, 36 BI CON, 42 BI TRT, 44 BT CON, and 44 BT TRT. For the steers that met the filtering requirements, the average number of gas flux visits per treatment were as follows: 140 visits/steer for BI CON, 146 visits/steer for BI TRT, 117 visits/steer for BT CON, and 164 visits/steer for BT TRT.

In addition to the collection of CH_4, CO_2, H_2, and O_2 gas flux, CH_4 as a proportion of gross energy intake (GEI)(Y_m), CH_4 as a proportion of DMI (MY), and CH_4 as a proportion of ADG (EI) in Phase 2, was calculated using Equation 2, 3, and 4 respectively.

Equation 2:

$$Ym, \%\ GEI = \frac{Gaseous\ Energy\ Loss, mcal/g}{GEI,\ mcal/g} \times 100$$

Equation 3:

$$MY, \frac{g}{kg} = \frac{CH_4, g}{DMI, kg}$$

Equation 4:

$$EI, \frac{g}{kg} = \frac{CH_4, g}{ADG, kg}$$

Furthermore, CH_4 as a proportion of carcass gain in Phase 2 (EI_{cg}) was calculated using Equation 5 derived from Tatum et al. (2012) and Equation 6.

Equation 5:

$$Phase\ 2\ Estimated\ Carcass\ Gain, kg = Final\ HCW - (Estimated\ Beginning\ HCW = 0.2598 \times IBW^{1.1378})$$

Equation 6:

$$EI_{CG}, \frac{g}{kg} = \frac{CH_4, g}{Phase\ 2\ Estimated\ Carcass\ Gain, kg}$$

Carcass Characteristics

Following the collection of weights on d 180, steers were shipped to a commercial abattoir in Greeley, Colorado, approximately 48.3 km from the Colorado State University Agricultural Research, Education, and Development Center, for harvest. Harvest data was collected by a third party (Diamond T Livestock Services, Inc., Alliance, NE, USA). On the same day as slaughter, hot carcass weight (HCW) and liver abscess prevalence (scored as 0, A−, A, and A+; Brown et al., 1975) were assessed. Carcasses were chilled for 24 h at −4 °C. Approximately 24 h after slaughter, the carcasses were ribbed between the 12th and 13th ribs, and carcass data were collected via cameras, including 12th rib backfat thickness (FT), longissimus muscle area (LMA), and marbling score. Yield grade (YG) was calculated using the United States Department of Agriculture (USDA) YG equation with a standard kidney, pelvic, and heart fat percentage of 2.0 (USDA, 1997; Boykin et al., 2017). The USDA YG and quality grade (QG) for each carcass were assigned by a USDA grader at the commercial abattoir. Dressing percentage (DP) was calculated by dividing HCW by shrunk FBW and multiplying by 100.

Environment

Environmental data was collected using the publicly available CoAgMET service to acquire ambient air temperature (°C; T_a), relative humidity (%, RH), solar radiation, and wind speed data collected continuously throughout the experimental period from an on-site weather station (station no. ftc03) at the Colorado State University Agricultural Research, Education, and

Development Center (40.65°N, −105°E) located 9.7 km northeast of Fort Collins at an elevation of 1557.5 m. Temperature humidity index (THI) was calculated using T_a and RH in Equation 7, adapted from Thom (1959).

Equation 7:

$$\text{THI} = (0.8 \times \text{T}_\text{a}) + [(\text{RH} \div 100) \times (\text{T}_\text{a} - 14.4)] + 46.4$$

Descriptive statistics are reported for weather station data collected during the 180 d feeding period (Table 2). An average ambient temperature of 16 °C was exhibited, with an average minimum of approximately 4 °C and an average maximum of 31 °C. July was the hottest month, with an average temperature of 21 °C, exhibiting a minimum ambient temperature of approximately 10 °C and a maximum temperature of approximately 36 °C during the month. Relative humidity averaged 58%, with an average minimum of approximately 10% and an average maximum of 95% during the experimental period. Solar radiation averaged approximately 240 $W/m^{2,}$ and wind speed averaged approximately 2 m/s during the experimental period. Moreover, THI averaged 59, with an average minimum of 49 and an average maximum of 72 (Figure 1).

Statistical Analysis

The experimental design of Phase 1 of the experimental period was a randomized complete block design with a 2×2 factorial arrangement of treatments. Data were analyzed with R (R Core Team, 2021, v. 4.4.1) software using the lmer() function within the lme4 package to construct a linear mixed-effects model. The model diagnostics included testing for normal distribution of the error residuals via visual assessment of the histogram and Q-Q plot for each variable, as well as formally conducting the Shapiro-Wilk test, homogeneity of variance via visual assessment of the residual versus fitted values plot, and independence among observations which was ensured during the study design. The assumptions were adequately held.

For Phase 1, the fitted model was:

$$Y_{ijkl} = \mu + S_i + T_j + (ST)_{ij} + W_k + B_l + E_{ijkl}$$

Where Y_{ijkl} is the response variable; S_i is the fixed effect of sub-species; T_j is the fixed effect of treatment; $(ST)_{ij}$ is the interaction between sub-species and treatment; W_k is the fixed effect of initial body weight of the phase; B_l is the random effect of block; and E_{ijkl} is the experimental error.

The experimental design of Phase 2 of the experimental period was a completely randomized design with a 2×2 factorial arrangement of treatments. Data were analyzed with R (R Core Team, 2021, v. 4.4.1) software using the aov() function within the base R package to construct a linear effects model. The model diagnostics included testing for normal distribution of the error residuals, homogeneity of variance, and independence among observations using methodologies previously described. The assumptions were adequately held.

For Phase 2, the fitted model was:

$$Y_{ijk} = \mu + S_i + T_j + (ST)_{ij} + W_k + E_{ijk}$$

Where Y_{ijk} is the response variable; S_i is the fixed effect of sub-species; T_j is the fixed effect of treatment; $(ST)_{ij}$ is the interaction between sub-species and treatment; W_k is the fixed effect of initial body weight of the phase; and E_{ijk} is the experimental error.

Categorical data distributions were analyzed by logistic regression. The model was constructed using the glm() function of the base R package. Least-squares means were derived using the emmeans package in R, with Tukey's HSD adjustment. For Phase 1 pen was the experimental unit, and for Phase 2 individual animal was the experimental unit. Differences were declared significant at $P \leq 0.05$, and tendencies were discussed between $0.05 < P \leq 0.10$.

RESULTS

Growth Performance

In Phase 1, IBW did not differ ($P \geq 0.75$) by cattle sub-species or management treatment (Table 3). However, FBW differed ($P < 0.01$) by cattle sub-species and management treatment, with BT steers weighing more than BI steers and steers managed with the use of GPT having greater FBW than CON. There was a difference ($P < 0.01$) in ADG between cattle sub-species and management treatment, with BT steers having greater ADG compared to BI steers, and steers managed without the use of GPT having less ADG than steers managed with GPT. Even though DMI did not differ ($P = 0.35$) by management treatment, BT steers had greater ($P < 0.01$) DMI than BI steers on a total daily basis and as a percentage of BW. Furthermore, G:F also differed ($P < 0.01$) by cattle sub-species and management treatment, with BT steers having greater feed efficiency than BI steers and TRT steers having greater feed efficiency than CON steers.

In Phase 2, IBW differed ($P < 0.01$) by cattle sub-species and management treatment, with BT steers exhibiting greater IBW than BI steers and TRT steers exhibiting greater IBW than CON steers (Table 4). Additionally, FBW exhibited a sub-species × treatment interaction ($P < 0.01$), where the effect of using GPT on FBW was greater for BT steers than BI steers. Similarly, ADG had a sub-species × treatment interaction ($P < 0.01$), with the use of GPT resulting in a greater magnitude of difference in BT steers than BI steers. Moreover, DMI differed ($P < 0.01$) by sub-species and treatment, with BT steers having greater DMI than BI steers and steers managed with the use of GPT exhibiting greater DMI than steers managed without GPT. However, as a percentage of BW, DMI exhibited a sub-species × treatment interaction where the direction of the response to the use of GPT differed ($P = 0.01$) by sub-species. The use of GPT resulted in a greater magnitude of difference in DMI as a percentage of BW for BI steers, whereas in BT steers, DMI as a percentage of BW did not differ. Furthermore, G:F exhibited a sub-species × treatment interaction ($P = 0.02$), with the use of GPT exhibiting a greater magnitude of difference for BT steers versus BI steers.

Carcass Characteristics

Similar to FBW in Phase 2, HCW exhibited a sub-species × treatment interaction ($P = 0.05$; Table 5). The magnitude of difference in HCW between CON and TRT steers was greater for BT steers than for BI steers. Moreover, DP differed ($P \leq 0.04$) by cattle sub-species and management treatment, favoring BI steers and steers that were not managed with GPT. The backfat thickness of the carcass did not differ ($P \geq 0.18$) by cattle sub-species or management treatment. Additionally, LMA differed ($P < 0.01$) by cattle sub-species and management treatment. Steers managed with the use of GPT exhibited greater LMA than those managed without GPT, and BT steers had greater LMA than BI steers. Calculated YG did not differ ($P = 0.18$) by cattle sub-species but tended ($P = 0.06$) to be greater for CON steers compared to TRT steers. Marbling score exhibited a sub-species × treatment interaction ($P < 0.01$), where steers managed with GPT exhibited a greater decrease in marbling score than CON steers for BT when compared to BI steers, which did not exhibit a difference in marbling score between treatments.

When assessing YG distribution, the percent distribution of YG differed ($P < 0.01$) by sub-species for YG 1, 2, and 3 but did not differ ($P = 0.14$) by management treatment (Table 6). Carcasses of BI steers had a greater proportion of YG 1 and 2 when compared to BT. However, BT carcasses had a greater proportion of YG 3 carcasses than BI. For the proportion of YG 4 carcasses, a sub-species × treatment interaction was observed ($P = 0.02$), where BT TRT carcasses had a greater proportion of YG 4 carcasses compared to CON steers but did not differ by management treatment for BI steers. When observing the USDA QG carcass distribution, QG distribution differed ($P < 0.01$) by sub-species for USDA Prime, Choice, and Standard grades, as well as dark cutter carcass designations. Carcasses of BI steers had a greater ($P < 0.01$) proportion of USDA Standard QG. However, USDA Choice and USDA Prime QG carcasses were observed in greater ($P < 0.01$) proportions for BT than BI. Moreover, USDA Prime-graded carcasses also differed ($P < 0.01$) by treatment, with a greater proportion of CON carcasses grading USDA Prime than TRT for BT steers. Moreover, BI steers were observed to have a greater incidence of dark cutter carcasses than BT. The proportion of carcasses grading USDA Select had a sub-species × treatment interaction ($P < 0.01$).

Liver abscess prevalence was assessed, observing a difference ($P < 0.01$) in the proportion of non-abscessed livers between management treatments, with TRT steers having a greater proportion of non-abscessed livers than CON steers (Table 7). For A-minus liver scores, abscess prevalence differed ($P = 0.02$) by treatment, with CON having a greater proportion of A-minus scored livers compared to TRT. For A-scored livers, CON tended ($P = 0.08$) to have a greater proportion of A-scored livers than TRT. However, A-plus liver scores did not differ ($P = 0.11$) by treatment. Total abscess prevalence (0 vs. A-, A, and A+) differed ($P < 0.01$) by management treatment, with TRT steers exhibiting less abscessed livers than CON steers. Liver scores did not differ ($P \geq 0.27$) by cattle sub-species.

Gas Flux

Absolute emissions of CH_4, in g/d, differed ($P < 0.01$) by cattle sub-species, with BT steers emitting more CH_4 than BI steers (Table 8). Gas flux of CO_2 and O_2 also differed ($P < 0.01$) by cattle sub-species and management treatment. Moreover, H_2 emissions had a sub-species × treatment interaction ($P < 0.01$), where H_2 decreased when steers were managed with GPT for BT steers but increased when steers were managed with GPT for BI steers. Furthermore, the yield of CH_4, as a proportion of gross energy intake (Y_m), was greater ($P < 0.01$) for BT steers than for BI steers. Similar to Y_m, MY was greater ($P < 0.01$) for BT steers compared to BI steers, meaning more CH_4 was emitted per unit of feed intake by BT steers than BI steers. Conversely, EI exhibited a sub-species × treatment interaction ($P < 0.05$), with steers of both sub-species managed with GPT exhibiting a lesser EI than CON counterparts; however, BT steers exhibited a greater reduction in EI when compared to BI steers. Similarly, EI_{CG} had a sub-species × treatment interaction ($P = 0.02$), where the use of GPT decreased CH_4 emissions per unit of carcass gain, but a greater reduction in EI_{CG} was observed for BT steers between CON and TRT than for BI steers.

DISCUSSION

Growth Performance

Historically, BI breeds have received pushback from the beef feedlot and packing industries, primarily in regard to poor growth performance and carcass characteristics (Huffman et al., 1990). Historically the primary benefit of BI cattle has been their use in crossbreeding programs in the South and Southwest regions of the US, where the resulting offspring exhibit enhanced adaptability to the hot, humid climatic conditions (Paschal et al., 1995). Therefore, climatic conditions in which BI cattle have evolved differ from the climatic conditions of the experimental location in the present study. However, to garner more information regarding the sustainability tradeoffs of increasing the proportion of BI genetics in the US-fed cattle industry as an adaptation strategy for feeding cattle in increasingly warmer climates, the experimental location offers the ability to evaluate thermal extremes. Moreover, it would be beneficial to understand more about their feedlot growth performance compared to BT cattle, considering management with and without the use of GPT, to acknowledge any deviations from past observations while also incorporating current market niches (Cartwright, 1980; Boyles and Riley, 1991).

Ferrell and Jenkins (1998) documented that steer genotype can influence the rate of growth and G:F. When considering BI and BT comparative research trials, previous observations have reported that BT cattle consumed greater quantities of feed with greater feed efficiency than BI counterparts, generally corresponding to greater growth rates (Arthur et al., 1994; Ferrell and Jenkins, 1998; Elzo et al., 2009). Observations by Butler et al. (1956b) reported the growth performance advantage of BT cattle versus BI cattle when they were fed grain-based diets. It has been proposed that differences in growth performance between BT and BI cattle fed grain-based diets could be an outcome of evolution since BI cattle originated in tropical climates where feeding systems generally depend on poor-quality forage resources (Chaokaur et al., 2015). This idea was supported by research from Arthur et al. (1994), who observed that when growing steers were raised in different nutritional environments, BI steers gained more BW than BT counterparts on poor-quality pasture, but the inverse was observed when steers were placed on a good-quality pasture. Therefore, the previously described observations regarding greater rates of growth for BT steers relative to BI steers when fed a greater-quality diet would apply to the results of the present study where BT steers outperformed BI steers on a grain-based diet. The observed cattle sub-species difference is a necessary production challenge to consider in the application of increasing the proportion of BI genetics in feedlot systems where grain-based diets are commonly fed.

In Phase 1 of the current study, BT steers had approximately 35% greater DMI and 26% greater DMI as a percentage of BW, which resulted in 61% greater ADG and 32% greater G:F ratio on average compared to BI steers. The observed increase in ADG resulted in an average 17% increase in FBW in the first 84 d of the feeding period for BT steers when compared to BI steers. Growth performance observations reported in Phase 1 of the present study were consistent with observations in Phase 2. Differences in feed efficiency in Phases 1 and 2 between BT and BI steers could be attributed to differences in protein versus fat carcass accretion influenced by the stage of animal growth and proximity to mature body size in each phase (Owens et al., 1995). As an animal deposits more fat relative to protein, they may become less efficient due to fat deposition requiring more energy than protein deposition (Owens et al., 1995). Bidner et al. (2002) concluded that mature body size varies amongst breeds of cattle, with Angus reaching mature body size at lighter body weight than BI-influenced cattle, requiring fewer days on feed to reach a common backfat thickness. Additionally, Frish and Vercoe (1977) explained that as BI cattle evolved under poorer nutritional conditions, they were naturally selected for slower fasting metabolism (good survival ability) corresponding to less voluntary feed intake, resulting in decreased growth rates under good nutritional conditions relative to BT cattle. Available literature supports the suggestion that BI cattle, in general, have reduced maintenance requirements relative to BT cattle (van der Merwe and van Rooyen, 1980; Solis et al., 1988). It has been proposed that differences in maintenance requirements, among other factors like feed intake habits and behavior, gastrointestinal tract capacity, and confinement sensitivity, may, in part, contribute to differences in feed efficiency between BI and BT cattle (Butler et al., 1956b; Cartwright, 1980). Future research regarding differences in feeding behavior amongst breeds would provide further insight to aid in the identification of feed management practices for different breeds when fed in confinement.

According to NASEM (2016), beef steers managed without the use of anabolic implants are predicted to have 6% less feed intake than steers managed with anabolic implants, and steers managed without monensin are predicted to have 3% greater intake than steers managed with monensin. Interestingly, when specifically considering BT steers in the present study, while Phase 1 observed DMI as a percentage of body weight was greater than predicted (2.3 vs. 2.2; Eq. 10-4; NASEM, 2016), Phase 2 DMI on a percentage of body weight basis was slightly less than predicted (1.9 vs. 2.0; Eq. 10-4; NASEM, 2016). When evaluating CH_4 emission classification and ranking of non-implanted and implanted steers in the finishing phase of beef production, data from Vargas et al. (2025) yielded an average DMI as a percentage of BW of 1.7, when steers were fed a similar finishing diet to the present study, with net energy of gain being 1.32 Mcal/ kg DM. However, Vargas et al. (2025) utilized a stocking rate of approximately 5 steers per SF bunk systems. In Phase 2 of the present study, steers were managed for *ad libitum* intake where bunk competition was equal for all treatments with approximately 10 steers per SF bunk system across treatments. The stocking rate for SF bunk systems varies in the literature but is generally between 4 to 8 hd/bunk systems, with the manufacturer's general recommendation between 7 and 8 hd/bunk system for feedlot steers (Holder et al., 2022; Fuerniss et al., 2023; Vargas et al., 2024). In the present study, the authors acknowledge an aggressive stocking rate, but do not believe stocking rate inhibited *ad libitum* feed intake due to evaluation of daily orts, which averaged approximately 6 kg per bunk at 0700 hours. Additionally, the ratio of bunk use to total possible bunk time was calculated, yielding a ratio of 0.43 for BT steers. The application of this ratio can be interpreted as there was approximately 14 h/SF bunk/d of excess bunk time when bunks were not used but could have been used. However, appropriate stocking rate methodologies should be investigated for SF bunk systems to improve consistency in equipment utilization across research environments and management methodologies to allow for improved comparisons amongsts the literature. These methodologies are critical to evaluate due to the relationship between level of feed intake and CH_4 emissions (Johnson and Johnson, 1995).

Beyond the influence of cattle sub-species, previous research by Reichhardt et al. (2023) observed that different cattle breeds responded differently to the use of GPT. This observation was demonstrated in the present study. In Phase 1, steers managed with GPT had 21% greater ADG and 22% greater G:F compared to steers managed without GPT. However, the use of GPT did not affect DMI or DMI as a percentage of BW in Phase 1. Conversely, in Phase 2, when steers were managed with GPT, TRT steers consumed, on average, 7% more feed per day than CON steers. Moreover, when DMI was reported as a percentage of BW in Phase 2, the use of GPT increased DMI by 7% for BI steers, while BT steers were observed to have a 0.5% decrease in DMI. Furthermore, in Phase 2, ADG was greater for steers managed with GPT, with the use of GPT resulting in a 34% increase in ADG for BI steers and a 38% increase in ADG for BT steers. Greater ADG in TRT steers corresponded to a 7% increase in FBW of BI steers and 9% increase in FBW for BT steers relative to CON counterparts.

In a meta-analysis of modern technologies commonly used in beef production, Wileman et al. (2009) reported that cattle that were implanted with anabolic implants had a 17% improvement in ADG and a 9% improvement in G:F when compared to non-implanted cattle. Lean et al. (2014) conducted a meta-analysis investigating growth performance characteristics of feedlot cattle supplemented with a beta-adrenergic agonist and reported ractopamine hydrochloride supplementation resulted in approximately an 8 kg increase in BW and 0.19 kg/d increase in ADG with no substantial difference in DMI compared to non-supplemented cattle. Similarly, increases in ADG from 11.1 to 27.4% in steers supplemented with ractopamine hydrochloride at 200 mg for the final 28 d of the feeding period have been previously reported (Laudert et al., 2005a; Schroeder et al., 2005b). Ractopamine hydrochloride supplementation has consistently been demonstrated to increase BW, ADG, and G:F in beef cattle when compared to non-supplemented counterparts (Scramlin et al., 2010; Genther-Schroeder et al., 2016; Bryant et al., 2020). Moreover, Duffield et al. (2012) conducted a meta-analysis investigating the effect of monensin supplementation on beef cattle growth performance and observed a 6.4% increase in G:F influenced by a 3% decrease in DMI and a 2.5% increase in ADG. A lack of research exists considering the synergistic effects of managing cattle using multiple GPT. Despite the use of multiple GPT in the present study and the inability to identify how each GPT may be influencing the observed growth performance, this research clearly demonstrates that the use of GPT resulted in greater FBW, ADG, and G:F in feedlot steers. However, the present study also highlights that cattle of differing sub-species do not elicit the same growth performance response when using GPT, highlighting that GPT use may be more valuable to use in certain cattle sub-species from a cattle husbandry standpoint compared to others.

Carcass Characteristics

In general, BI cattle have been reported to have less desirable carcass quality attributes, primarily marbling, when compared to BT cattle breeds, resulting in scrutiny from the fed cattle and beef packing sectors of the beef industry (Huffman et al., 1990). Preceding observations would suggest that BT cattle generally exhibit greater HCW, YG, and marbling scores when compared to BI contemporaries (Adams et al., 1982; Lunt et al., 1985; Paschal et al., 1995; Gruber et al., 2007). In the present study, the effect of GPT use on HCW differed between cattle sub-species. Steers of the BI sub-species that were managed with GPT had an observed 5% greater HCW than counterparts managed without GPT. However, steers of the BT sub-species managed with GPT exhibited an 8% greater HCW than counterparts managed without GPT. Observations of the present study are consistent with preceding research investigating GPT use. Bryant et al. (2010) observed that steers receiving an anabolic implant exhibited greater HCW when compared to non-implanted steers. Moreover, Bryant et al. (2020) observed that cattle receiving ractopamine hydrochloride exhibited greater HCW than non-supplemented cattle. Furthermore, in the present study, BT steers had a 4% greater LMA than BI steers, and the use of GPT increased LMA, with TRT steers having a 6% greater LMA than CON. Previously documented observations have exhibited that both anabolic implants and beta-adrenergic agonists increase LMA compared to non-implanted and non-supplemented cattle, respectively (Bryant et al., 2010; Bryant et al., 2020).

The effect of GPT on marbling score differed by sub-species, with BT CON steers obtaining marbling scores 22% greater than BT TRT steers, but no difference was observed for marbling scores for BI steers between treatments. However, despite a greater decrease in marbling scores between CON and TRT BT steers, BT TRT steers still yielded greater marbling scores than BI steers. Huffman et al. (1990) reported that when the percentage of BI influence was 50% or greater in feedlot cattle, smaller marbling scores and subsequent poorer quality grades were observed relative to BT steers. In the present study, the majority of BI carcasses were observed to grade USDA Standard and USDA Select, whereas the majority of BT carcasses were observed to grade USDA Choice or USDA Prime. Additionally, BI carcasses exhibited a greater proportion of dark cutter grades than BT. When evaluating Brahman steers that received an anabolic implant, Smith et al. (2007) observed an average marbling score of 390.3, corresponding to the Select USDA quality grade. This observation is concurrent with observations of the present study, with BI steers that were receiving GPT exhibiting an average marbling score of 329, corresponding to the USDA Select quality grade. Ultimately, despite both cattle sub-species demonstrating an increase in HCW and LMA with the use of GPT, observations suggest that the cattle sub-species did not respond to the same magnitude to the use of GPT. Furthermore, BI steers demonstrated to have less intramuscular fat deposition, regardless the use of GPT or not, when compared to BT steers.

Liver abscess prevalence is not only an economic concern in the fed cattle industry but also an animal welfare concern that impacts the sustainability of beef cattle production systems (Baier et al., 2020). In the present study, tylosin phosphate was supplemented in the diet of TRT steers. When considering total liver abscess prevalence (0 vs. A-, A, and A+), CON steers that did not receive tylosin phosphate had approximately three times greater liver abscess prevalence than TRT steers. Similarly to the present study, Müller et al. (2018) observed that 21.4% of cattle that did not receive supplemental tylosin phosphate presented with liver abscesses, whereas only 7.8% of cattle that received supplemental tylosin phosphate had liver abscesses. Data from Müller et al. (2018) demonstrated that cattle that did not receive tylosin phosphate had approximately three times greater liver abscess prevalence than cattle receiving tylosin phosphate, which is similar to the present study. Moreover, the DP of cattle is an economic factor of great importance (Butler et al., 1956b). In previous comparative studies, reports vary regarding the outcome of DP between cattle sub-species (BT vs. BI). Some reports suggest that BT cattle have shown an advantage in DP (Adams et al., 1982), while others suggest BI cattle have shown an advantage in DP (Black et al., 1934; Butler et al., 1956a; Butler et al., 1956b). Black et al. (1934) reported that steers that were approximately half Brahman had DP between 2-4% greater than BT steers. In the present study, BI steers had a DP 2% greater than BT steers. Differences in digestive tract size between BI and BT steers offer a plausible explanation for differences in DP between sub-species, as BI steers have been observed to have smaller digestive tracts relative to BT steers (Black et al., 1934).

However, the present study observed that BT CON steers had greater DP than TRT steers, whereas previous research suggested that the use of GPT should result in greater DP (Bryant et al., 2010; Ross et al., 2021). Future research should evaluate economic tradeoffs in carcass quality and quantity for BT and BI steers to understand the margin of relative profitability that could be anticipated if the proportion of BI cattle in the US-fed cattle industry increases in the future.

Gas Flux

Increasing atmospheric concentrations of GHG and their contribution to global warming have led scientists to examine their sources of origin (Johnson and Johnson, 1995; Shibata and Terada, 2010). Methane is a short-lived but potent GHG that has a variety of biogenic and anthropogenic sources, one of which is through enteric CH_4 production from wild and domesticated ruminant species. In an assessment of global ruminant CH_4 emissions measurements, it was observed that most cattle studies assessed BT cattle, with only 12% of cattle studies evaluating BI cattle (Della Rosa et al., 2022). However, BI cattle represent more than half the global cattle population and are the predominant cattle sub-species in tropical and subtropical climatic zones around the world (Utsunomiya et al. 2019). Given the genomic, phenotypic, and feed consumption differences, it is logical to postulate that there may be differences in CH_4 emissions between BI and BT sub-species of cattle. Collection of data that is representative of the global cattle population is critical to evaluate in order to improve GHG emissions inventories and aid in more accurately representing the contribution of CH_4 at a global and national scale from cattle (Della Rosa et al., 2022).

In the present study, absolute CH_4 emissions differed by sub-species, with BT steers producing approximately 33% more CH_4, in g/d, than BI steers. Therefore, from an absolute emissions standpoint, the present study has observed that BI steers emitted less CH_4 than BT steers.

Nonetheless, many factors influence CH_4 emissions from cattle, requiring further investigation in the context of these two sub-species. Some factors that have been extensively described include the level of feed intake, type and quality of carbohydrates in the diet, feed processing, additives (*e.g.*, lipids, ionophores), and alterations in the ruminal microflora (*e.g.*, defaunation) (Johnson and Johnson, 1995; Shibata and Terada et al., 2010; Beauchemin et al., 2022). Therefore, it is logical to postulate that the difference in absolute CH_4 emissions between BT and BI steers in the current study were influenced by feed intake differences. However, to the authors' knowledge, this is the first study of its kind and future comparative CH_4 evaluations of BI and BT cattle may consider investigation of the rumen microbial community and rate of digestion to isolate factors influencing CH_4 production differences between cattle sub-species beyond feed intake in order to identify potential interventions and mitigation opportunities.

A complexity that exists in the realm of animal science regarding gas flux measurement is the interpretation of absolute gas production versus gas production yield per unit of input or output (Beauchemin et al., 2022). Beyond enteric CH_4 emissions from beef cattle being an environmental sustainability concern, these emissions are also problematic with respect to energy utilization efficiency (Chaokaur et al., 2015). According to Johnson and Johnson (1995), cattle typically emit 6% of their gross energy intake (GEI) as eructated CH_4, but emissions may vary between 2-12%. National inventories for enteric CH_4 are calculated in accordance with the Intergovernmental Panel on Climate Change guidelines, where the CH_4 conversion factor, also known as Y_m, is a critical metric used to assess the potential extent of global warming and to estimate total enteric CH_4 emissions (Steinfeld et al., 2006; Gerber et al., 2013; Houghton et al., 1996). The Intergovernmental Panel on Climate Change Tier 1 methodology involves multiplying the cattle population by a standard emissions factor, whereas the Tier 2 methodology involves a more complex approach (Beauchemin and McGinn, 2006). For cattle, Tier 2 emission factors are estimated based on the GEI and the corresponding standardized Y_m based on the production system (grazing vs. confinement) (IPCC, 2006). The Intergovernmental Panel on Climate Change guidelines for a Tier 2 approach set a default Y_m of 3% for feedlot cattle fed steam-flaked corn in North America, a value generated predominately utilizing BT gas flux measurements (IPCC, 2006).

In the present study, Y_m ranged from approximately 4.8% to 5.4%. Between sub-species, BT steers were observed to have approximately 8% greater Y_m when compared to BI steers. Johnson et al. (1993) extrapolated chamber measurements to typical diets at common levels of intake that occur across US beef cattle herds and suggested that Y_m varies from approximately 5.8% to 6.5% for all categories and classes except for the unique feedlot situation, where grain-based diets are fed, in which typical Y_m may drop to approximately 3%. The present study if 3% Y_m was used to represent emissions from this population of beef cattle fed a concentrate-based diet during the feedlot phase of production, emissions would be underestimated. Moreover, the present study observed that when considering MY, BT steers had approximately 8% greater MY than that of BI. Schutt et al. (2009) observed that BI cattle have a greater efficiency of energy capture relative to BT. Therefore, evolution differences in the digestive anatomy and physiology between the sub-species may be a plausible reason why Y_m and MY are less for BI steers relative to BT. However, when CH_4 was expressed as the mass of CH_4 emitted per unit gain, the impact of managing steers with or without GPT resulted in a greater magnitude of difference in EI for BT steers than BI steers. For BT steers, forgoing the use of GPT resulted in 41% greater EI, whereas for BI steers, this difference was 25%. Moreover, when considering EI_{CG}, the use of GPT resulted in a 16% decrease in CH_4 per unit carcass gain in BI steers and a 32% decrease in BT steers. These observations emphasize the halo effect that occurs throughout value-based systems, like agri-food systems, where the sustainability of a product is attributed to the perceived health and safety benefit, which necessitates education and communication of the sustainability advantages of using GPT in cattle production systems. Moreover, the contradiction of absolute emissions versus emissions efficiency conceptualizes the complexity of interpreting the sustainability of beef cattle production. From strictly an environmental standpoint, limiting total emissions is of high priority. However, when simultaneously considering topics of food security and production efficiency, balancing yield and environmental impact is crucial (Place, 2024).

CONCLUSION

The purpose of this study was to evaluate the growth performance and gas flux of BT and BI steers managed with and without the use of GPT in summer feedlot conditions. From a growth performance perspective, BT steers grew faster and ate more, finishing at heavier FBW when compared to BI steers. Moreover, GPT increased DMI and ADG, resulting in greater feed efficiency, lending to heavier FBW. Additionally, observations demonstrated that the effect of GPT differed by sub-species for ADG, G:F, FBW, HCW, and marbling score. For gas flux, BI steers emitted less CH_4 than BT steers and had a lesser yield of CH_4 as a proportion of GEI and DMI due to the consumption of less feed. However, GPT reduced GHG emissions when expressed per unit of gain or beef produced, with a greater decrease demonstrated between treatments in BT versus BI steers. Furthermore, BT steers produced greater quality carcasses, highlighting a limitation of BI steers in a consumer demand-driven industry.

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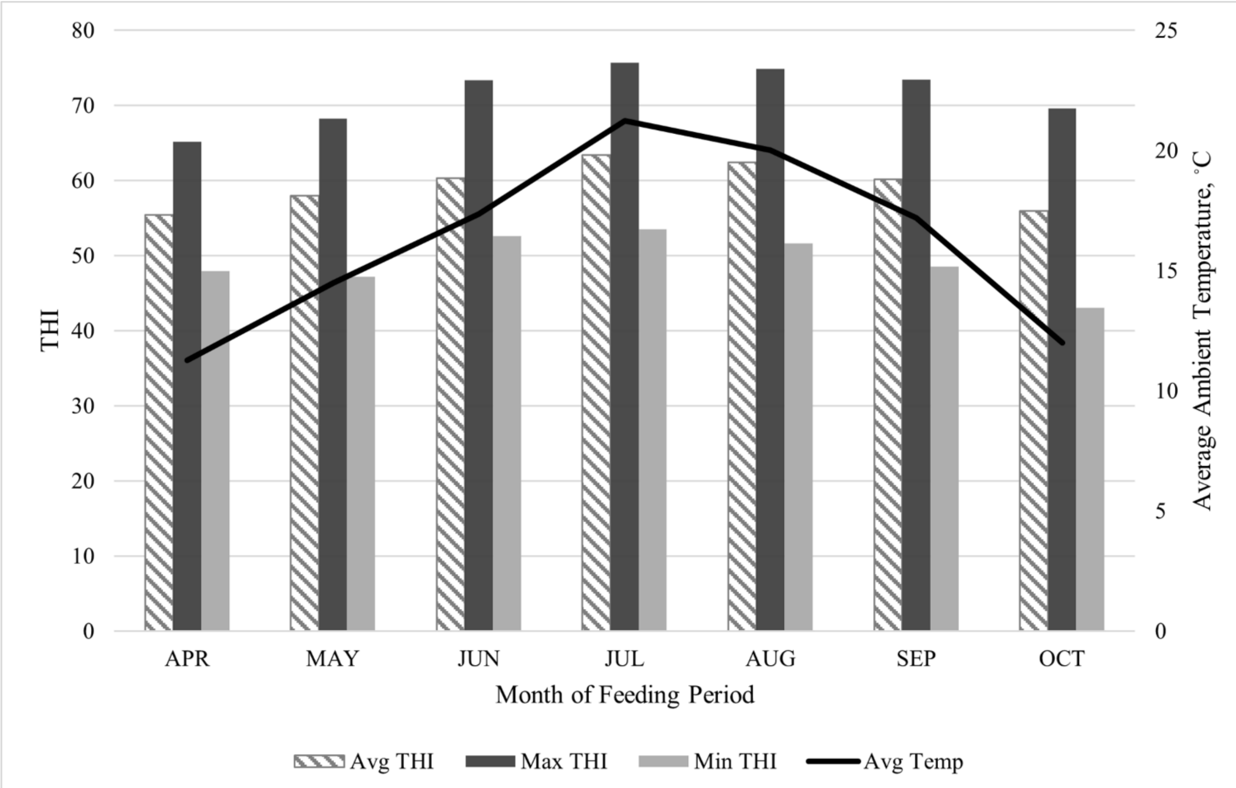

Figure 2.1. Temperature humidity index (THI) and average ambient temperature during the 180d feeding period in summer feedlot conditions: THI = $(0.8 \times T_a) + [(RH/100) \times (T_a - 14.4)] + 46.4$ (Thom, 1959), where Ta is ambient temperature (°C), and RH is relative humidity (%); Min=minimum; Max=maximum; Avg=average.

Table 2.1. Dietary ingredients and analyzed chemical composition of the diets.

Item[1]	Diet			
	Starter	Step 1	Step 2	Finish
Ingredient, % DM				
Steam-flaked corn	30.0	44.0	55.0	65.0
Corn silage	50.0	40.0	30.0	20.0
Distillers grains w/ solubles	13.5	9.5	8.5	7.0
Molasses-based supplement	3.3	3.3	3.3	4.0
Mineral and vitamin supplement	3.2	3.2	3.2	4.0
Chemical Composition, DM basis[2]				
DM, %	48.2	49.2	59.9	65.7
CP, %	15.0	14.8	13.4	14.2
ADF, %	13.3	11.4	8.6	8.9
NDF, %	19.9	17.8	14.3	14.3
Lignin, %	2.7	2.8	2.5	2.3
Starch, %	45.1	49.8	57.0	57.6
Ash, %	6.8	5.3	4.0	4.6
TDN, %	77.0	79.0	82.0	82.0
NE_m, Mcal/kg	1.89	1.95	2.02	2.03
NE_g, Mcal/kg	1.25	1.31	1.37	1.38
GE, Mcal/kg	4.49	4.45	4.51	4.44

[1]DM = dry matter; CP = crude protein; ADF = acid detergent fiber; NDF = neutral detergent fiber; TDN = total digestible nutrients; NE_m = net energy for maintenance; NE_g = net energy for gain; GE = gross energy.

[2]Dietary composition was determined via wet chemistry.

Table 2.2. Descriptive statistics of environmental variables measured during the 180 d feeding period in summer feedlot conditions.

Month[2]	Environmental Variable[1]							
	T_a			RH			WS	SR
	Min[4]	Max[4]	Mean	Min[4]	Max[4]	Mean	Mean	Mean
APR	2.56	22.11	11.24	0.19	0.76	0.41	3.3	290.22
MAY	1.87	26.77	14.48	0.07	0.97	0.63	2.5	237.27
JUN	8.31	33.07	17.30	0.09	0.99	0.69	2.1	262.44
JUL	9.77	35.61	21.20	0.11	0.99	0.60	1.9	257.23
AUG	7.09	34.81	19.89	0.15	0.97	0.64	1.7	238.79
SEP	3.55	32.40	17.19	0.09	0.98	0.54	1.8	218.74
OCT	-3.54	28.40	12.01	0.09	0.97	0.52	2.1	174.80

[1]T_a= ambient air temperature, °C; RH= relative humidity, %; WS= wind speed, m/s; SR= solar radiation, W/m^2.
[2]Month of 180 d feeding period, were APR= April, MAY= May, JUN= June, JUL= July, AUG= August, SEP= September, OCT= October.
[3]Min= Minimum, Max= Maximum.

Table 2.3. Growth performance of finishing *Bos taurus* and *Bos indicus* steers managed with and without the use of growth-promoting technologies during Phase 1 (0 to 83 days) in summer feedlot conditions.

Item[1]	*Bos indicus*		*Bos taurus*		SEM[3]	S[4]	T[4]	S×T[4]
	CON[2]	TRT[2]	CON[2]	TRT[2]				
n, pen	5	5	5	5	-	-	-	-
IBW, kg	343	341	342	340	12.4	0.90	0.75	0.98
FBW, kg	417	445	497	521	3.9	<0.01	<0.01	0.65
ADG, kg	0.90	1.23	1.84	2.14	0.046	<0.01	<0.01	0.67
DMI, kg/d	6.77	7.07	9.86	9.85	0.222	<0.01	0.35	0.49
DMI_{BW}, % of BW	1.77	1.80	2.35	2.29	0.048	<0.01	0.74	0.39
G:F	0.132	0.174	0.192	0.230	0.0029	<0.01	<0.01	0.45

[1]IBW = initial body weight; FBW = final body weight; ADG = average daily gain; DMI = dry matter intake; DMI_{BW} = dry matter intake according to the body weight; G:F = gain to feed ratio.
[2]CON= managed without the use of growth-promoting technologies, TRT = cattle managed with the use of growth-promoting technologies.
[3]SEM= standard error of the mean.
[4]S = main effect cattle sub-species; T = main effect management treatment; S×T = interaction between cattle sub-species and management treatment.

Table 2.4. Growth performance of finishing *Bos taurus* and *Bos indicus* steers managed with and without growth-promoting technologies during Phase 2 (84 to 180 days) in summer feedlot conditions.

Item[1]	*Bos indicus*		*Bos taurus*		SEM[3]	S[4]	T[4]	S×T[4]
	CON[2]	TRT[2]	CON[2]	TRT[2]				
n, animal	49	49	46	50	-	-	-	-
IBW, kg	420	443	495	519	5.9	<0.01	<0.01	0.95
FBW, kg	564[c]	604[b]	594[b]	652[a]	4.1	<0.01	<0.01	<0.01
ADG, kg	0.99[c]	1.40[b]	1.30[b]	1.91[a]	0.043	<0.01	<0.01	<0.01
DMI, kg/d	7.45	8.30	9.91	10.40	0.167	<0.01	<0.01	0.20
DMI_{BW}, % BW	1.43[b]	1.54[b]	1.86[a]	1.85[a]	0.029	<0.01	0.48	0.01
G:F	0.134[b]	0.170[a]	0.129[b]	0.182[a]	0.0043	0.53	<0.01	0.02

[1]IBW = initial body weight; FBW = final body weight; ADG = average daily gain; DMI = dry matter intake; DMI_{BW} = dry matter intake according to the body weight; G:F = gain to feed ratio.
[2]CON= managed without the use of growth-promoting technologies, TRT = cattle managed with the use of growth-promoting technologies.
[3]SEM= standard error of the mean.
[4]S = main effect cattle sub-species; T = main effect management treatment; S×T = interaction between cattle sub-species and management treatment.
[a,b,c] Means in the same row within main effect that do not have a common superscript letter differ, $P \leq 0.05$.

Table 2.5. Carcass data from *Bos taurus* and *Bos indicus* steers managed with and without the use of growth-promoting technologies following a 180 day feeding period in summer feedlot conditions.

Item[1]	*Bos indicus*		*Bos taurus*		SEM[3]	S[4]	T[4]	S×T[4]
	CON[2]	TRT[2]	CON[2]	TRT[2]				
n, animal	49	49	46	50	-	-	-	-
HCW, kg	361[c]	381[b]	375[b]	405[a]	2.9	<0.01	<0.01	0.05
DP, %	63.9	63.2	63.1	62.0	0.28	0.04	<0.01	0.58
FT, cm	1.22	1.13	1.22	1.21	0.052	0.96	0.18	0.40
LMA, cm^2	82.5	88.2	86.3	91.1	1.18	<0.01	<0.01	0.66
Calculated YG	3.05	2.85	2.98	2.98	0.087	0.61	0.06	0.19
Marbling Score	344[c]	329[c]	600[a]	483[b]	15.1	<0.01	<0.01	<0.01

[1]HCW = hot carcass weight; DP = dressing percentage; FT = Back fat measured between the 12th and 13th rib after 24 h chill; LMA = longissimus muscle area; YG = yield grade; Marbling score scale: 300 = slight, 400 = small, 500 = modest, 600 = moderate.
[2]Experimental management treatment; CON= managed without the use of growth-promoting technology, TRT = cattle managed with the use of growth-promoting technology.
[3]SEM= standard error of the mean.
[4]S = main effect cattle sub-species; T = main effect management treatment; S×T = interaction between cattle sub-species and management treatment.
[a,b,c]Means in the same row within main effect that do not have a common superscript letter differ, $P \leq 0.05$

Table 2.6. United State Department of Agriculture yield and quality grade distribution for *Bos taurus* and *Bos indicus* steers managed with and without the use of growth-promoting technologies following a 180 day feeding period in summer feedlot conditions.

Item[1]	*Bos indicus*		*Bos taurus*		SEM[3]	S[4]	T[4]	S×T[4]
	CON[2]	TRT[2]	CON[2]	TRT[2]				
n, animal	49	49	46	50	-	-	-	-
USDA YG, %								
YG 1	20.4	20.4	0.0	0.0	5.76	<0.01	1.00	1.00
YG 2	46.9	57.1	28.3	20.0	7.13	<0.01	0.87	0.17
YG 3	28.6	22.4	69.6	70.0	6.78	<0.01	0.65	0.59
YG 4	4.1[ab]	0.0[b]	2.2[b]	10.0[a]	4.24	0.14	0.52	0.02
USDA QG, %								
Prime	0.0	0.0	26.1	6.0	6.47	<0.01	<0.01	1.00
Choice	20.4	10.2	73.9	80.0	6.47	<0.01	0.70	0.13
Select	40.8[a]	44.9[a]	0.0[b]	14.0[b]	7.11	<0.01	0.11	<0.01
Standard	32.7	38.8	0.0	0.0	6.96	<0.01	0.53	1.00
Dark Cutter	6.1	6.1	0.0	0.0	3.42	<0.01	1.00	1.00

[1] Quality grade marketing category determined by expert marbling score: USDA Prime = Slightly Abundant^{0} to Abundant^{99}; USDA Choice = Small^{0} to Moderate^{99}; USDA Select = Slight^{0} to Slight^{99}; USDA Standard = Traces^{0} to Traces^{99}.

[2]Experimental management treatment; CON= managed without the use of growth-promoting technologies, TRT = cattle managed with the use of growth-promoting technologies.

[3]SEM= standard error of the mean.

[4]S = main effect cattle sub-species; T = main effect management treatment; S×T = interaction between cattle sub-species and management treatment.

[a,b,c]Means in the same row within main effect that do not have a common superscript letter differ, $P \leq 0.05$.

Table 2.7. Liver abscess prevalence data from *Bos taurus* and *Bos indicus* steers managed with and without the use of growth-promoting technologies following a 180 day feeding period in summer feedlot conditions.

Item[1]	*Bos indicus*		*Bos taurus*		SEM[3]	S[4]	T[4]	S×T[4]
	CON[2]	TRT[2]	CON[2]	TRT[2]				
n, animal	49	49	46	50	-	-	-	-
Liver Abscess Prevalence, %								
0	81.6	93.9	73.9	92.0	6.47	0.34	<0.01	0.86
A-	2.0	0.0	6.5	0.0	3.64	0.27	0.02	1.00
A	6.1	0.0	4.4	2.0	3.42	0.95	0.08	0.22
A+	10.2	6.1	15.2	6.0	5.30	0.56	0.11	0.65
Total Abscess Prevalence	18.4	6.1	26.1	8.0	6.47	0.34	<0.01	0.86

[1]Liver abscess prevalence where; 0 = non-abscessed liver; A- = one or two small abscesses; A = two to four small, active abscesses; A+ = one or more large, active abscesses, including any open and adhered abscesses.
[2]Experimental management treatment; CON= managed without the use of growth-promoting technologies, TRT = cattle managed with the use of growth-promoting technologies.
[3]SEM= standard error of the mean.
[4]S = main effect cattle sub-species; T = main effect management treatment; S×T = interaction between cattle sub-species and management treatment.

Table 2.8. Gas flux of finishing *Bos taurus* and *Bos indicus* steers managed with and without the use of growth-promoting technologies during Phase 2 (84 to 180 days) in summer feedlot conditions.

Item[1]	*Bos indicus*		*Bos taurus*		SEM[3]	S[4]	T[4]	S×T[4]
	CON[2]	TRT[2]	CON[2]	TRT[2]				
n, animal	36	42	44	44	-	-	-	-
AHCS visits, *n*	140	146	117	164	-	-	-	-
DMI, kg/d	7.51	8.33	9.96	10.47	0.198	<0.01	<0.01	0.32
ADG, kg	0.97[c]	1.35[b]	1.32[b]	1.93[a]	0.050	<0.01	<0.01	<0.01
CH_4, g/d	123	133	179	180	5.5	<0.01	0.13	0.28
CO_2, g/d	7062	7604	9927	10244	143.0	<0.01	<0.01	0.32
O_2, g/d	5069	5455	6754	7215	92.3	<0.01	<0.01	0.61
H_2, g/d	0.78[c]	1.03[b]	1.45[a]	1.07[bc]	0.076	<0.01	0.22	<0.01
Y_m, % GEI	4.92	4.81	5.43	5.12	0.190	<0.01	0.21	0.52
MY, g CH_4/kg DMI	16.5	16.1	18.1	17.1	0.63	<0.01	0.21	0.53
EI, g CH_4/kg ADG	131.1[a]	101.9[b]	140.7[a]	92.8[b]	5.98	0.05	<0.01	0.05
EI_{CG}, g CH_4/kg CG	1.72[b]	1.47[b]	2.04[a]	1.48[b]	0.084	<0.01	<0.01	0.02

[1]AHCS = automated head chamber system; DMI = dry matter intake; ADG = average daily gain; CH_4 = methane; CO_2 = carbon dioxide; O_2 = oxygen; H_2 = hydrogen; Y_m= CH_4 emitted as a percent of gross energy intake (GEI); MY = methane yield; EI = emissions intensity; EICG = emissions intensity for carcass gain .

[2]Experimental management treatment; CON= managed without the use of growth-promoting technology, TRT = cattle managed with the use of growth-promoting technology.

[3]SEM= standard error of the mean.

[4]S = main effect cattle sub-species; T = main effect management treatment; S×T = interaction between cattle sub-species and management treatment.

[a,b,c]Means in the same row within main effect that do not have a common superscript letter differ, $P \leq 0.05$.

CHAPTER 3- EVALUATION OF CATTLE SUB-SPECIES AND GROWTH-PROMOTING TECHNOLOGY ON GROWTH PERFORMANCE, CARCASS CHARACTERISTICS, AND ENTERIC GAS FLUX OF STEERS FINISHED IN WINTER FEEDLOT CONDITIONS[2]

INTRODUCTION

As climate change progresses, there is a growing need to emphasize both climate mitigation and adaptation to combat increasingly severe, interconnected, and often irreversible climate impacts that disrupt supply chains (Pörtner et al., 2022). Beef cattle production systems are simultaneously vulnerable to the impacts of climate change and contributors to the progression. In the United States (US), enteric methane (CH_4) emissions are the largest source of emissions from beef cattle and comprise approximately 2 percent of total US greenhouse gas (GHG) emissions (EPA, 2024). Conversely, an increasing concern among US beef producers is the impact that a changing climate can have on animal performance and economic well-being, threatening the long-term viability of the beef industry (Capper and Hayes, 2012; Rojas-Dowing et al., 2017). To address plausible opportunities for mitigation and adaptation in the beef supply chain, cattle selection (Reichhardt et al., 2023) and managing beef cattle with growth-promoting technology (GPT; Capper and Hayes, 2012) have been proposed.

Beef cattle production in the US occurs across a large range of climatic zones from subtropical to temperate. To address increasingly variable and extreme thermal conditions, researchers have investigated the potential benefits of increasing the proportion of *Bos taurus indicus* (BI) cattle in

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[2] Schilling-Hazlett, A.K., K.R. Stackhouse-Lawson, T.C. Bryant, S.E. Place, J.P. Ritten, J.J. Vargas, I.A. Reis, E.C. Martins, M.A. Swenson, E.N. Burke, R.K. Campion, C. Velasquez, A.M. Shadbolt, and P.H.V. Carvalho. 2025. Evaluation of cattle sub-species and growth-promoting technology on growth performance, carcass characteristics, and enteric gas flux of steers finished in winter feedlot conditions. J. Anim. Sci. doi:10.1093/jas/skaf448.

the US cattle herd. In the US, BI cattle were first introduced to the Gulf Coast region to improve adaptability of beef cattle to the subtropical environmental conditions (Cartwright, 1980; Huffman et al., 1990). The greatest advantage of BI cattle in the US has been realized in crossbreeding programs, where heterosis contributes to improved production characteristics while enhancing tolerance to heat, disease, and parasites, particularly in the southern and southeastern US where cattle are exposed to hot, humid climates and poor quality forages (Paschal et al., 1995). Most BI cattle in the US were imported from Brazil, although their ancestral origin is India, in contrast to *Bos taurus taurus* (BT) cattle which are of European origin (Sanders, 1980). Morphological traits that distinguish BI from BT cattle include the cervico-thoracic hump, large pendulous ears, and excessive skin along the ventral body surface, chest, and neck (Utsunomiya et al., 2019). Beyond physical characteristics, BI and BT cattle differ in several important biological and production characteristics, including (1) heat and cold tolerance, (2) reproduction, (3) growth and maturation rates, (4) temperament, and (5) complementarity in crossbreeding systems (Cartwright, 1980). As a result of these differences, economic (*i.e.*, growth performance and carcass quality) and social concerns (*i.e.*, consumer acceptance of meat quality, and cattle temperament) have been documented for BI cattle (Boyles and Riley, 1991; Voisinet et al., 1997; Wright et al., 2018).

Still, an eminent need exists to identify adaptive strategies for beef cattle production systems as most regions are projected to experience increased frequency and severity of extreme heat events relative to the 1950s, and decreased frequency and severity of cold extremes (IPCC, 2021). Already, migratory shifts in the number of cattle and beef operations are apparent with cattle inventory trends reporting cattle moving northward to the central part of the US as well as into more concentrated operations (Fancher et al., 2025). Before recommendations to increase the proportion of BI cattle are explored, it is important to garner more information regarding their feedlot growth performance and carcass characteristics in more temperate regions (Cartwright, 1980). Additionally, improved growth performance, which can be achieved via the use of GPT, is suggested to be one of the most effective mitigation strategies to decrease GHG emissions from beef production per unit of feed consumed and product produced (Boadi et al., 2004; Monteny et al., 2006; Capper and Hayes, 2012; Stackhouse et al., 2012). Despite potential productivity and efficiency improvements resulting from the use of GPT, previous research has reported that different cattle breeds may respond differently to GPT (Reichhardt et al., 2023). Therefore, it is important to quantify differences in the effect of GPT to best inform future cattle selection and management decisions.

Further, it is important to quantify individual gas flux measurements from BI and BT cattle managed with and without the use of GPT in a temperate geographic region representative of where the US cattle herd is currently concentrated, to understand the impact of GHG emissions from the fed cattle sector. The objectives of the present study were to evaluate enteric gas flux of CH_4, carbon dioxide (CO_2), oxygen (O_2), and hydrogen (H_2), growth performance, and carcass characteristics of BI and BT sub-species of cattle managed with and without the use of anabolic implants, an in-feed antibiotic, ionophore, and beta-adrenergic agonist in a temperate climate in winter feedlot conditions. The authors hypothesized that BT steers and steers managed with GPT would exhibit greater growth performance, primarily due to greater feed intake and feed efficiency compared to BI steers and steers not managed with GPT. Predicted differences in growth performance were hypothesized to influence enteric gas flux emissions, where cattle that consumed more feed were expected to exhibit greater CH_4 emissions; thus, BT steers were expected to produce more CH_4 than BI steers.

MATERIALS AND METHODS

This experiment was conducted at the Colorado State University Agricultural Research, Education, and Development Center experiment station in Fort Collins, CO, from October 2023 to April 2024, consisting of a 180 d feeding period divided into two consecutive phases. All procedures involving animals were approved by the Colorado State University Institutional Animal Care and Use Committee (protocol no. 3712). All animals evaluated in the present study were sourced in two lots by a commercial cattle feeder, where lot one was comprised of BT steers from Montana and lot two of BI steers sourced from Texas. All steers were allotted 38 d to acclimate to the research facility prior to study initiation.

Environmental Conditions

Environmental variables were collected using the publicly available CoAgMET service to acquire ambient air temperature (°C; T_a), relative humidity (%, RH), solar radiation (W/m^2, SR), precipitation (mm, P), and wind speed (WS, m/s). Data were collected continuously throughout the experimental period from an on-site weather station (station no. ftc03) located 9.7 km northeast of Fort Collins at an elevation of 1557.5 m at the Colorado State University Agricultural Research, Education, and Development Center (40.65◦N, −105◦E).

Weather station data collected during the 180 d feeding period is presented in Table 1. An average T_a of 2.2 °C was exhibited, with a minimum of -30.2 °C and a maximum of 28.2 °C. January was the coldest month, with an average T_a of -4.2 °C, exhibiting a minimum of -30.2 °C and a maximum of 16 °C. Average RH during the feeding period was 56.8%, with a minimum of 7.9% and an average maximum of 98.7% during the experimental period. Moreover, average SR, WS, and P were 135.6 W/m^2, 2.5 m/s, and 0.02 mm/month, respectively, during the experimental period.

Animals and Experimental Design

Animals consisted of 100 BI (Brahman) yearling steers (initial body weight [IBW] = 364 ± 22 kg) and 100 BT (Angus) yearling steers (IBW = 323 ± 17 kg). Steers of each sub-species were randomly assigned to a management treatment, managed with GPT (GPT+) or without GPT (GPT-), in a 2 × 2 factorial arrangement. Steers in GPT+ received an anabolic implant on 0 d (100 mg trenbolone acetate/14 mg estradiol benzoate; Synovex Choice, Zoetis, Parsippany, NJ, USA) and 84 d (200 mg trenbolone acetate/28 mg estradiol benzoate; Synovex Plus, Zoetis). Steers in GPT+ also received an in-feed ionophore (35 g/ton on dry matter [DM] basis; monensin, Rumensin, Elanco, Greenfield, IN, USA) and antibiotic (7 g/ton on DM basis; tylosin, Tylan, Elanco) from d 0 to 180. Moreover, GPT+ steers received an in-feed beta-adrenergic agonist during the last 42 d of the feeding period (27 g/ton on DM basis; ractopamine hydrochloride, Actogain, Zoetis), allowing for a 2 d withdrawal period prior to harvest. The GPT- steers did not receive any of the above-listed GPT.

Regardless of management treatment and cattle sub-species, all steers were vaccinated with 2 mL Bovi-Shield GOLD 5 (Bovine rhinotracheitis-virus diarrhea-parainfluenza 3-respiratory syncytial virus vaccine, Zoetis), 2 mL Ultrachoice 8 (clostridial vaccine, Zoetis), Dectomax (doramectin, Zoetis), and orally drenched with Valbazen (albendazole, Zoetis) within 48 h post arrival to the feedlot. All cattle received a radio frequency identification tag (Allflex, USA Inc., Dallas, TX, USA) placed in the animal's left ear on the same processing date.

Steers were fed for 180 d in two consecutive phases. In Phase 1 (d 0 to 83), steers were housed in 10-hd research pens (7 m × 40 m). Steers were blocked by weight and randomly assigned to a pen, where the pen was considered the experimental unit (10 steers/pen; 5 pens/treatment). Each pen was equipped with a concrete feed bunk (30 cm/steer), a 3 m × 7 m concrete bunk pad, and an automatic waterer (model no. C250, Cancrete Cattle Waterer, Advanced Agri-Direct Inc. York, NE, USA). In Phase 2 (d 84 to 180), steers receiving the same treatment were moved and randomly assigned to 1 of the 4 Climate Smart Research Pens (15 m × 43 m) for the remaining 96 d of the experimental period, where the experimental unit was considered the individual animal (50 steers/treatment). Each Climate Smart Research Pen housed 50 steers/pen (1 pen/treatment), equipped with one GreenFeed automated head chamber system (AHCS, C-Lock, Rapid City, SD, USA), five SmartFeed bunk systems (C-Lock, Rapid City, SD, USA), two automatic waterers, a concrete bunk pad (15 m × 3 m), and a metal roof (15 m × 3 m) covering the SmartFeed bunk systems, AHCS, and approximately 7% of the pen surface.

Steers were monitored daily throughout the experimental period by trained personnel who evaluated fresh feed and water allocation, cattle health, locomotion, and clinical signs of disease. Steers exhibiting signs of respiratory disease, confirmed by a licensed on-site veterinarian, were removed from the pen to assess rectal body temperature and body weight (BW). Cattle with body temperatures greater than 39.4 °C were classified as clinically ill. All steers deemed clinically ill by the licensed on-site veterinarian were treated according to the appropriate treatment protocol prescribed by the on-site licensed veterinarian and immediately returned to their pen of origin. Any cattle deemed clinically ill or treated by the licensed on-site veterinarian were removed from the experiment. All treatments were managed according to the same animal health protocols. Following the completion of the experimental period, a total of 8 steers were removed from data analysis due to injury or illness: 4 BT GPT+ and 4 BT GPT-.

Feed Management and Intake

All steers were transitioned to the final finishing diet after a 21 d adaptation from a starter diet to a finishing diet, including two intermediate step-up diets (Table 2). Since some GPT were delivered in the diet, specific feed mixing and delivery protocols were implemented to prevent cross-contamination between the two rations throughout the experimental period. At the start of each feeding, the feed truck mixer was purged by mixing and delivering a standard ration to clean the equipment. Following this cleaning procedure, the GPT- ration was batched, mixed, and delivered first, after which the GPT+ ration was batched, mixed, and delivered.

Feed samples of each treatment ration were collected weekly, dried at 65 °C for a minimum of 48 h to determine DM and ground to pass through a 2 mm screen (Wiley Mill, Model 4; Arthur H. Thomas Co., Philadelphia, PA, USA) and preserved at room temperature. After the completion of the experimental period, feed samples of each treatment ration were composited and analyzed at a commercial laboratory using a wet chemistry package (Ration Balancer Plus with Gross Energy and Starch, Dairy One, Ithaca, NY, USA). Acid detergent fiber analysis was conducted following ANKOM Technology Method 14, and neutral detergent fiber analysis was conducted following ANKOM Technology Method 15 (ANKOM Technology, Macedon, NY, USA). Analysis of lignin was determined following ANKOM Technology Method 9 using a DaisyII Incubator (ANKOM Technology, Macedon, NY, USA). Crude protein analysis was determined via combustion and determination of ash used the AOAC Official Method 942.05- Ash for Animal Feed. Gross energy was determined using bomb calorimetry. Due to no significant difference in chemical analysis of the two treatment rations, average composition is reported.

During Phase 1, slick-bunk management was utilized to manage feed delivery to the feed bunk, and feed intake data was averaged daily on an animal-per-pen basis. Daily feed allocation per pen was divided by steer/pen, averaged by week, and multiplied by the percent DM of the total mixed ration (TMR) to determine weekly dry matter intake (DMI). Cattle removed from the study were documented to ensure DMI was calculated on a steer/pen basis and adjusted for the number of animals remaining in each pen following the removal of a steer from the study. During Phase 2, individual animal feed intake was determined utilizing SmartFeed bunk systems, and *ad libitum* bunk management was utilized to manage feed delivery. All cattle underwent a 7 d acclimation period to the SmartFeed bunk systems before the initiation of data collection. Feed intake data collected during the acclimation period were not used in the data analysis. The SmartFeed bunk systems were calibrated at the beginning and end of the experimental period and every 7 d during the experimental period. Following the conclusion of the experimental period, raw feeding events were downloaded from the manufacturer's online software. Feeding events that were flagged by the manufacturer (*e.g.*, unallocated feed or nonsensical eating rate), exceeded 3600 s in duration, and/or were greater than 10 kg mass difference were omitted from data analysis (approximately 47,000 events removed in total). Feeding events were then summed by day and averaged by week to determine weekly as-fed feed intake. As-fed feed intake was converted to DMI by multiplying by the percent DM of the TMR. To determine the average DMI for each phase, weekly DMI was averaged over the feeding period. During Phase 2 of the experimental period, DMI from alfalfa pellet drops from the AHCS were added to the TMR daily intake to determine total daily DMI. In addition to total daily DMI in Phases 1 and 2, DMI as a percentage of BW (DMI_{BW}) was calculated for each phase using Equation 1.

Equation 1:

$$DMI_{BW}, \%\,BW = \frac{DMI, kg}{BW, kg} \times 100$$

Growth Performance

Steers were individually weighed using a hydraulic squeeze chute (Model no. SHEW10497, Silencer, Moly Manufacturing Inc., Lorraine, KS, USA) equipped with an electronic weighing system (ID5000, Tru-Test Inc., Mineral Wells, TX, USA) on two consecutive days at the beginning of the experiment (d −1 and 0) to determine IBW and at the end (d 179 and 180) of the experimental period to determine final BW (FBW). In addition to IBW and FBW, steers were weighed every 28 d during the experimental period. Experimental mid-point BW, collected on d 84, was used as the FBW for Phase 1 and IBW for Phase 2. Weight data collected were reduced by 4% to account for digestive tract fill (*i.e.*, shrunk body weights [SBW]; NASEM, 2016). The SBW from each time point, every 28 d, was used to obtain cattle average daily gain (ADG) by subtracting the SBW of the previous time point from the SBW of the current time point and then dividing by the number of days between the two weight collection time points.

Gas Flux

Each Climate Smart Research Pen contained one AHCS for the collection of gas flux (*i.e.*, CH_4, CO_2, and H_2 emissions, and O_2 consumption). Steers were exposed to the AHCS during an acclimation period of 7 d before the initiation of data collection. The headbox extension panels (*i.e.*, wings) were placed on the AHCS system on d 3 of the acclimation period. On d 5 of the acclimation period, cattle panels were used to create an alley in front of the AHCS to ensure only one animal at a time had access to the AHCS. Measurements collected during the acclimation period were not included in the data analysis. Throughout the study, steers were allowed to visit the AHCS system up to 6 visits/d, with a minimum of 4 h between each visit. The AHCS was programmed to allow consumption of up to 6 drops of alfalfa pellets per visit (approximately 38 g as fed/drop), with drops occurring every 30 s while a steer was utilizing the AHCS system. These configuration settings encouraged an even distribution of AHCS visits for each steer throughout the day, capturing the diurnal variation in gas flux, and ensuring each steer remained at the AHCS for a minimum duration of 2 min during gas flux sample collection (Vargas et al., 2024).

To ensure proper functioning and performance of the AHCS, CO_2 recovery tests were performed at the beginning, end, and every 28 d throughout the experimental period to gravimetrically calibrate the AHCS. Additionally, zero and span calibrations of the CH_4, CO_2, H_2, and O_2 gas analyzers were performed every 3 d via an autocalibration system located onboard the AHCS. Raw collection data was validated by the AHCS manufacturer, which included checking head proximity, visit length, and airflow, as well as providing corrections for wind. Data was excluded when the length of the visit was less than 2 min, greater than 8 min, and the airflow was less than 26 L/s (Arthur et al., 2017; Gunter and Beck, 2018). Steers were excluded from the analysis of data if the total number of visits collected throughout Phase 2 was less than 40 (Beck et al., 2024). Of the 192 steers, excluding the 8 steers that were removed from the trial for health-related reasons, 149 steers met the filtering requirements to be included in the gas flux data analysis (44 BT GPT+, 37 BI GPT+, 40 BT GPT-, and 28 BI GPT-). For the steers that met the filtering requirements, the average number of gas flux visits per treatment was as follows: 151 visits/steer for BT GPT+, 148 visits/steer for BI GPT+, 109 visits/steer for BT GPT-, and 71 visits/steer for BI GPT-.

In addition to the collection of CH_4, CO_2, H_2, and O_2 gas flux, CH_4 conversion rate (Y_m) was calculate as the energy emitted as CH_4 relative to gross energy intake (GEI), CH_4 yield (MY) was calculated as the amount of CH_4 relative to DMI, and CH_4 intensity (EI) was calculated as the amount of CH_4 relative the ADG in Phase 2, using Equation 2, 3, and 4 respectively.

Equation 2:

$$Ym, \%\, GEI = \frac{Energy\ Emitted\ as\ CH_4,\ \ Mcal/kg}{GEI,\ \ Mcal/kg} \times 100$$

Equation 3:

$$MY, \frac{g}{kg} = \frac{CH_4, g}{DMI, kg}$$

Equation 4:

$$EI, \frac{g}{kg} = \frac{CH_4, g}{ADG, kg}$$

Carcass Characteristics

Following the collection of weights on d 180, steers were shipped to a commercial abattoir in Fort Morgan, Colorado, approximately 150 km from the Colorado State University Agricultural Research, Education, and Development Center, for harvest. Harvest data were collected by a third party (Diamond T Livestock Services, Inc., Alliance, NE, USA). On the same day as slaughter, HCW, and liver abscess prevalence (scored as 0, A−, A, and A+; Brown et al., 1975) were assessed. Carcasses were chilled for 24 h at −4 °C. Approximately 24 h after slaughter, the carcasses were ribbed between the 12^{th} and 13^{th} ribs, and carcass data were assessed via cameras, including 12^{th} rib backfat thickness (FT), longissimus muscle area (LMA), and marbling score. Yield grade (YG) was calculated using the United States Department of Agriculture (USDA) YG equation with a standard kidney, pelvic, and heart fat percentage of 2.0 (USDA, 1997; Boykin et al., 2017). The USDA YG and quality grade (QG) for each carcass was assigned by a USDA grader at the commercial abattoir. The "No Roll" QG indicates carcasses that did not receive an official USDA QG or YG at the commercial abattoir due to quality below the USDA Select grade; however, these carcasses were still inspected for wholesomeness and safety for human consumption. All carcass characteristics were assessed for "No Roll" carcasses and included in data analysis. Dressing percentage (DP) was calculated using Equation 5.

Equation 5:

$$Dressing\ percentage, \% = \frac{HCW,\ \ kg}{Final\ SBW,\ \ kg} \times 100$$

Statistical Analysis

In Phase 1, the experimental design was a randomized complete block design with a 2 × 2 factorial arrangement of the treatments. Data were analyzed with R (R Core Team, 2021, v. 4.4.1) software using the lmer() function within the lme4 package to construct a linear mixed-effects model. The model diagnostics included testing for normal distribution of the error residuals via visual assessment of the histogram and Q-Q plot for each variable, as well as formally conducting the Shapiro-Wilk test, homogeneity of variance via visual assessment of the residual versus fitted values plot, and independence among observations which was ensured during the study design. The assumptions were adequately held.

For Phase 1, the fitted model was:

$$Y_{ijkl} = \mu + S_i + T_j + (ST)_{ij} + W_k + B_l + E_{ijkl}$$

Where Y_{ijkl} is the response variable; S_i is the fixed effect of sub-species; T_j is the fixed effect of treatment; $(ST)_{ij}$ is the interaction between sub-species and treatment; W_k is the fixed effect of IBW of the phase; B_l is the random effect of block; and E_{ijkl} is the experimental error.

The experimental design of Phase 2 was a completely randomized design with a 2 × 2 factorial arrangement of treatments. Data were analyzed with R (R Core Team, 2021, v. 4.4.1) software using the aov() function within the base R package to construct a linear effects model. The model diagnostics included testing for normal distribution of the error residuals, homogeneity of variance, and independence among observations using methodologies previously described. The assumptions were adequately held.

For Phase 2, the fitted model was:

$$Y_{ijk} = \mu + S_i + T_j + (ST)_{ij} + W_k + E_{ijk}$$

Where Y_{ijk} is the response variable; S_i is the fixed effect of sub-species; T_j is the fixed effect of treatment; $(ST)_{ij}$ is the interaction between sub-species and treatment; W_k is the fixed effect of IBW of the phase; and E_{ijk} is the experimental error.

Categorical data distributions were analyzed by logistic regression. The model was constructed using the glm() function of the base R package. Least-squares means were derived using the emmeans package in R, with Tukey's HSD adjustment. For Phase 1, pen was the experimental unit, and for Phase 2, individual animal was the experimental unit. Differences were declared significant at $P \leq 0.05$.

RESULTS

Growth Performance

In Phase 1, no interaction ($P > 0.23$) was observed between cattle sub-species × treatment for growth performance variables (Table 3). However, IBW, differed ($P < 0.01$) by cattle sub-species, with BI steers being heavier than BT steers at the beginning of the experiment. Moreover, BT cattle had greater ($P < 0.01$) DMI, DMI_{BW}, G:F, ADG, and FBW compared to BI steers. Although IBW was different between cattle sub-species, it did not differ ($P = 0.98$) by management treatment. No treatment effect ($P = 0.19$) was observed for DMI. However, GPT+ steers had greater ($P \leq 0.02$) FBW, ADG, and G:F compared to GPT- steers for Phase 1.

In Phase 2, no interaction ($P > 0.14$) was observed between cattle sub-species × treatment for IBW, ADG, and FBW (Table 4). However, an interaction ($P \leq 0.04$) was observed for DMI,

DMI_{BW} and G:F. The use of GPT resulted in a greater increase in DMI between GPT- and GPT+ for BI steers compared to BT steers. Similarly, DMI_{BW} had a cattle sub-species × treatment interaction ($P < 0.01$) where a greater magnitude of difference was observed in DMI_{BW} between GPT- and GPT+ for BI steers compared to BT steers. Moreover, G:F had a cattle sub-species × treatment interaction ($P < 0.01$) where a greater increase in feed efficiency was observed in BI steers between GPT+ and GPT- than BT counterparts. Furthermore, Phase 2 IBW, ADG, and FBW differed ($P < 0.001$) by cattle sub-species, with BT steers exhibiting greater IBW, ADG, and subsequent FBW than BI steers. Moreover, IBW, ADG, and FBW differed ($P < 0.01$) by treatment with GPT+ steers starting at heavier body weights, gaining more, and finishing at heavier FBW than GPT- steers.

Carcass Characteristics

No interaction ($P \geq 0.07$) was observed between cattle sub-species × treatment for DP, FT, LMA, calculated YG, or liver abscess prevalence (Table 5). However, an interaction ($P \leq 0.03$) was observed for HCW and marbling score. For HCW a greater magnitude of difference was observed between GPT- and GPT+ for BI steers compared to BT. Moreover, the use of GPT in BT steers reduced marbling scores compared to GPT-, while no difference was observed in marbling score for BI cattle between the two treatments. Cattle sub-species differed ($P < 0.01$) for DP, FT, LMA, and calculated YG; however, no difference ($P \geq 0.21$) between cattle sub-species was observed for liver abscess prevalence. Steers of BI origin exhibited greater DP and LMA, while BT steers had greater FT and calculated YG. Management treatment did not differ ($P \geq 0.30$) for DP, FT, calculated YG, or liver abscess prevalence, but differed ($P < 0.01$) for LMA. The use of GPT yielded greater LMA than when managed without GPT.

When assessing YG and QG percentage distributions, no interactions ($P \geq 0.20$) were observed between cattle sub-species × treatment (Table 6). However, the percentage distribution of YG differed ($P \leq 0.02$) by cattle sub-species for YG 1, 2, 3, 4, and No Roll carcasses. Carcasses of BI steers had a greater proportion of No Roll, YG 1, and YG 2 when compared to BT. However, BT had a greater proportion of YG 3 and YG 4 carcasses. Additionally, the percentage distribution of USDA QG differed ($P < 0.01$) by cattle sub-species for Prime, Choice, Select, and No Roll grades. Carcasses of BI steers had a greater ($P < 0.01$) proportion of No Roll and Select QG, while Choice and Prime QG were observed in greater ($P < 0.01$) proportions for BT. Moreover, the percentage distribution for USDA YG differed ($P \leq 0.04$) by treatment for YG 3 and 4 but did not differ ($P \geq 0.30$) by treatment for YG 1, 2, or No Roll, or USDA QG. A greater proportion of YG 3 carcasses were observed for GPT+ compared to GPT-, and a greater proportion of YG 4 carcasses were observed in GPT- compared to GPT+.

Gas Flux

No interaction ($P \geq 0.08$) was observed between cattle sub-species × treatment for CH_4, CO_2, H_2, Y_m, or MY (Table 7). However, an interaction ($P \leq 0.01$) was observed between cattle sub-species × treatment for O_2 and EI. Consumption of O_2 was greater for GPT+ compared to GPT- for BT steers, while no difference was observed between treatments for BI steers. Additionally, when GPT was utilized for BI steers EI decreased compared to BI steers managed without GPT; however, no effect was observed between treatments for BT steers. Total daily emissions of CH_4 differed ($P < 0.01$) by cattle sub-species and were greater for BT steers than BI steers. Additionally, emissions of CO_2 and H_2 differed ($P < 0.01$) by cattle sub-species, with BT steers exhibiting greater emissions of CO_2 and H_2 than BI steers. Moreover, Y_m and MY, were greater ($P < 0.01$) for BI steers than for BT steers, meaning more CH_4 was emitted per unit of GEI and DMI by BI steers than BT steers, respectively. Gas flux measurements did not differ ($P \geq 0.09$) by treatment.

DISCUSSION

Growth Performance

Instances of extreme heat have become more frequent and severe across most land regions since the 1950s, while cold extremes have become less frequent and severe (IPCC, 2021). However, the migration of the US cattle population to more temperate regions, which may experience both hot and cold extremes, garners research assessing the sustainability of cattle selection and management adaptations to ensure the resiliency of the supply chain (Fancher et al., 2025). While BI breeds have received attention regarding their utilization in environments that are experiencing increased ambient temperatures, these breeds have historically received criticism from the beef feedlot and packing industries, primarily regarding poor growth performance and carcass characteristics (Huffman et al., 1990). Another consideration regarding BI breeds is their efficiency of utilizing poor quality diets as opposed to good quality diets (Butler et al., 1956b; Arthur et al., 1994; Chaokaur, 2015), which is a production challenge to consider in the application of increasing the proportion of BI cattle in feedlot systems where good quality diets (*i.e.*, grain-based rations) are commonly fed.

When considering BI and BT comparative research trials, few have conducted comparative evaluations of straight-bred BT and BI cattle, likely because it has been recommended that the greatest advantage of BI cattle lies in the crossbreeding programs in the south and southwest regions of the US where the crosses are well adapted to the hot, humid climate (Paschal et al., 1995). Preceding literature would indicate that BT cattle consume greater quantities of feed

(Boyles, 1991; Ferrell and Jenkins, 1998) with greater feed efficiency (Boyles and Riley, 1991) than BI counterparts, generally corresponding to greater growth rates in BT cattle (Butler et al., 1956b; Lunt et al., 1985; Boyles, 1991). Boyles (1991) reported that following a 184 d feeding period in cold environmental conditions, Angus steers gained 17 kg more than Brahman-Angus steers, resulting in Angus steers having greater ADG throughout the feeding period; however, ADG of Angus steers diminished slightly over time compared to Brahman-Angus steers. Moreover, Boyles and Riley (1991) reported that BI × BT steers consumed 0.2% less feed as a percentage of BW than Angus steers. Similarly, Butler et al. (1956b) reported that BT steers had greater ADG than BI × BT steers, and Lunt et al (1985) observed that Angus steers finished at heavier BW than Brahman steers following a 168 d feeding period on a commercial finishing diet. These observations align with the present study. In the present study, BI steers entered Phase 1 with an IBW approximately 12% greater than BT steers. Nonetheless, by the end of the phase, BT steers weighed approximately 19% more, reflecting their greater ADG, DMI, and G:F. Given that BI steers were approximately 42 kg heavier at study initiation, it is possible they were older than BT steers, despite all cattle being sourced as yearlings. Importantly, IBW was included in the statistical model to account for such differences. Furthermore, growth performance observations in Phase 2 were consistent with Phase 1, although responses to GPT diverged between sub-species for DMI and G:F.

To the authors' knowledge, previous comparative studies of BT and BI steers have not specifically reported differences in illness or removal rate. In the present study, 8% of BT steers (4% GPT+ and 4% GPT-) were removed due to illness, whereas no BI steers were removed. From a systems perspective, this observation has potential implications for overall production efficiency and warrants further investigation. Notably, despite the 8% removal rate, BT steers still yielded more total live weight than BI steers (28,520 vs. 28,025 kg), indicating that growth performance advantages of BT cattle remained evident. Nevertheless, the higher removal rate in BT steers may offset some of these advantages under commercial conditions, particularly in environments where health and adaptability challenges are more pronounced. Moreover, many factors influence the health of a feedlot steer such as preconditioning (Duff and Galyean, 2007). Since steers in this study were sourced from different regions of the US, differences in preconditioning and prior management could potentially contributed to the observed removal rates. Moreover, it should be acknowledged that the present study was conducted at 1557.5 m above sea level. It has been reported that in Angus cattle even moderate elevations (1,200 to 1,600 m) can cause physiological alterations that predispose cattle to disease (Pauling et al., 2018). Future investigations should further examine breed-specific differences in altitude-induced pathophysiological responses that may influence feedlot health and survival.

Recent research has suggested that different cattle breed types may respond differently to GPT (Reichhardt et al., 2021; Rivero et al., 2021). However, determining optimal cattle management with GPT across different cattle sub-species in feedlots in temperate climates is needed (Reichhardt et al., 2023). When investigating cattle of BI × BT and BT origin in temperate environmental conditions, Reichhardt et al. (2023) reported steers receiving an anabolic implant had greater DMI and G:F, corresponding to greater ADG. It is well accepted that of the GPT available in cattle production systems, anabolic implants increase DMI, G:F, and ADG of feedlot steers (Duckett and Pratt, 2014; Smith and Johnson, 2020). Duckett and Pratt (2014) observed that cattle managed with anabolic implants consumed 6% more feed with 6% greater feed efficiency, resulting in an 18% improvement in ADG. Similarly, Fox et al. (1992) reported that cattle not receiving an anabolic implant can be expected to have DMI 6% less than implanted cattle. When considering ionophores, Duffield et al. (2012) conducted a meta-analysis investigating the effect of monensin on beef cattle growth performance and observed a 6.4% increase in G:F, a 3% decrease in DMI, and a 2.5% increase in ADG. Furthermore, when considering beta-adrenergic agonists, ractopamine hydrochloride supplementation has consistently been demonstrated to increase BW, ADG, and G:F when compared to non-supplemented beef steers, regardless of use in combination with anabolic implants, tylosin phosphate, and/or monensin (Scramlin et al., 2010; Genther-Schroeder et al., 2016; Bryant et al., 2010 & 2020). The present study observed a 33% improvement in ADG and 31% improvement in G:F between GPT+ and GPT- steers, which is similar to the 37.8% improvement in ADG and 33.3% improvement in G:F between BT steers receiving tylosin phosphate, monensin, an anabolic implant, and a beta-adrenergic agonist versus not receiving any GPT (Maxwell et al., 2015). A difference in the magnitude of response when multiple GPT are utilized may suggest the potential for an additive or synergetic response when cattle are managed with a combination of GPT. Additive responses are plausible considering different mechanisms of actions between various GPT, since some GPT (*i.e.*, ionophores and antibiotics) alter the rumen microbial composition, while others (*i.e.*, anabolic implants and beta-adrenergic agonists) modulate post-absorptive metabolism (NASEM, 2016). Despite the use of multiple GPT in the present study and the inability to identify how each GPT may be influencing the observed growth performance, observations clearly demonstrate that the use of GPT resulted in greater FBW, ADG, and G:F in feedlot steers. However, the present study also highlights that cattle of differing sub-species do not elicit the same growth performance response when using GPT, suggesting that GPT use may be more valuable to use in certain sub-species of cattle, which may require further investigation.

On a total daily basis, BT steers consumed more feed than BI steers during both Phase 1 (9.8 vs. 7.0 kg/d) and Phase 2 (11.3 vs. 7.6 kg/d). Within BT steers, average DMI did not differ between those managed without or with growth-promoting technologies (GPT− and GPT+; 11.3 kg/d). In a model-based analysis, Crawford et al. (2022) reported that feedlot cattle finished without GPT had a mean DMI of 8.9 kg/d at a FBW of 602 kg, compared with 9.0 kg/d at an FBW of 655 kg for cattle managed with GPT (*i.e.*, anabolic implants, ionophores, and β-adrenergic agonists). Similarly, Stackhouse-Lawson et al. (2013) observed no significant differences in DMI between steers of comparable FBW managed without GPT (10.2 kg/d) and with GPT (10.6 kg/d; *i.e.*, anabolic implants, ionophores, and β-adrenergic agonists). Compared to Crawford et al. (2022) and Stackhouse-Lawson et al. (2013), the greater DMI observed in the present experiment may reflect increased maintenance energy requirements associated with winter feeding conditions (NASEM, 2016).

When considering differences in growth performance and efficiency between BI and BT steers in winter conditions, the greater surface area of BI cattle could be detrimental to conserving heat (Boyles, 1985). For most animals reared in the US in outside environments, maintenance energy requirements will decrease when the environmental temperature is greater than 20°C but increase when less than 20°C (NASEM, 2016; BR-CORTE, 2023). Despite recommendations that BI cattle require approximately 10% less energy than BT beef cattle (NASEM, 2016), Boyles (1985) concluded that net energy for maintenance (NE_m) requirements were reduced by approximately 6% for BI × BT steers compared to BT steers in thermoneutral conditions; but increased 9% for BI × BT steers compared to BT steers in cold stress conditions. Therefore, when more energy is partitioned to maintaining homeothermy, less energy is available for gain. Moreover, when an energy-dense diet is fed, BT steers generally gain weight more efficiently and at a faster rate than

BI steers, due to greater feed consumption relative to energy requirements for BT steers compared to BI steers (NASEM, 2016). Therefore, basic differences in energy partitioning offers a plausible explanation to differences in growth performance between BT and BI steers in the present study.

Carcass Characteristics

A concern with introducing BI genetics into the US beef herd in greater proportions is the resulting effects this transition may have on carcass quality (Huffman et al., 1990; Reichhardt et al., 2023). In the US, beef producers are typically paid on a grid system, resulting in YG and QG being pivotal (Schroeder et al, 2009). Previous research has recommended that when steers have at least 50% BI-influence, they will be unacceptable to the cattle feeder if quality grade is used to determine price at harvest (Boyles, 1985). Moreover, Butler et al. (1956b) observed that as diet quality increased, growth performance and quality grades of BT steers increased; but diet quality has little effect on growth performance and quality grades of BT × BI steers. Furthermore, despite Brahman-Angus steers having HCW an average 36.5 kg less than the present study, Boyles (1991) observed only 10% of Brahman-Angus steers graded USDA Choice, whereas 90% of Angus steers graded USDA Choice when cattle of similar age were evaluated during a 184 d finishing period, similar to the present study. Observations reported by Boyles and Riley (1991) are consistent with the present study where over 90% of BT steers and approximately 29% of BI steers graded USDA Choice. However, it is well known that BT crossbred or purebred steers are expected to exhibit superior meat quality attributes when compared to purebred BI steers (Butler et al., 1956b; Huffman et al., 1990; Goulart et al., 2020). Observations regarding differences in QG and associated marbling score between BT and BI steers may be due to greater selection pressure in BT cattle for economically relevant traits such as superior meat quality (Zayas and Mateescu, 2025). Therefore, in the present study it is reasonable to postulate that even if BI steers were finished to a common final body weight or backfat thickness as BT steers, they would still have less intramuscular fat.

Differences between cattle sub-species regarding intramuscular fat deposition were further confirmed by Reichhardt et al. (2023), stating that marbling score was influenced by cattle breed with BT exhibiting greater marbling scores than BI × BT crosses. In the present study, BT steers had greater marbling scores resulting in all BT carcasses grading USDA Choice or greater, whereas the majority of BI carcasses graded Select. However, the effect of GPT on marbling score differed by cattle sub-species, with the use of GPT resulting in a greater decrease in marbling score for BT steers compared to no observed difference for BI steers. When evaluating Brahman steers that received an anabolic implant, Smith et al. (2007) observed an average marbling score of approximately 390, corresponding to the Select USDA quality grade. This observation is consistent with observations of the present study, where BI steers that were receiving GPT had an average marbling score of 380, corresponding to the Select USDA quality grade. Beyond genetic selection and potential predisposition, differences in energetic efficiency previously discussed regarding growth performance may also be a factor influencing muscle versus fat deposition from a carcass standpoint.

In addition to BI carcasses generally having less intramuscular fat, the same has been observed regarding subcutaneous fat deposition. Boyles (1991) reported that when comparing steers of similar age and FBW (approximately 507 kg) harvested at 184 d on feed, Brahman-Angus steers had 0.5 cm less subcutaneous backfat at the 12^{th} rib. Moreover, Boyles and Riley (1991) reported that the LMA of Angus steers was approximately 5 cm^2 less than BI steers. These observations are consistent with the present study, where BT had approximately 0.3 cm greater FT and 6 cm^2 smaller LMA, corresponding to greater calculated YG. In the present study, BI steers produced a greater proportion of YG 1 (16% vs. 0%) and YG 2 (51% vs. 7%) carcasses, whereas BT steers produced more YG 3 (60% vs. 27%) and YG 4 (34% vs. 2%) carcasses. Differences in YG can logically be explained by differences in HCW, LMA , and FT between BT and BI steers. For BI steers, lesser calculated YG would be expected due to lighter HCW, less FT, and larger LMA; whereas, for BT steers greater calculated YG would be expected due to heavier HCW, greater FT, and smaller LMA. Boyles and Riley (1991) documented that BT steers had an average YG of 4.0 ± 0.3, while BI steers had an average YG of 3.0 ± 0.3, indicating nearly a fully yield grade difference between BT and BI steers finished at similar FBW and fed for 184 d in cold climatic conditions. These results are similar to the present study, where BT steers had an average calculated YG of approximately 3.5 while BI steers had an average calculated YG of approximately 2.7, demonstrating a similar difference between YG of BT and BI steers as reported by Boyles and Riley (1991). However, in the present study, BT steers were approximately 60 kg heavier after the 180 d feeding period, which may have contributed to some degree to differences in observed carcass characteristics. In the present study, steers were fed to a common number of days on feed rather than to a common compositional endpoint, consistent with approaches reported in the literature. Although, this decision was also influenced by funding constraints and resource availability.

Furthermore, LMA differed with the use of GPT, with GPT+ steers having 6 cm greater LMA than GPT- steers. Due to anabolic implants and beta-adrenergic agonists altering post-absorptive metabolism which influences the deposition of muscle protein (NASEM, 2016), this response was anticipated. In the present study, observations for HCW and LMA are consistent with preceding research investigating the effect of GPT use on carcass characteristics. Bryant et al. (2010) observed that steers receiving an anabolic implant exhibited greater HCW when compared to non-implanted steers, and Bryant et al. (2020) reported that cattle receiving ractopamine hydrochloride exhibited greater HCW than non-supplemented cattle. Additionally, these experiments observed increased LMA when anabolic implants and beta-adrenergic agonists were utilized (Bryant et al., 2010; Bryant et al., 2020).

The DP of cattle is an important and economically relevant factor (Butler et al., 1956b). In previous comparative studies, reports vary regarding the outcome of DP between cattle sub-species (BT vs. BI and BI × BT). Some reports suggest that BT cattle have shown an advantage in DP (Adams et al., 1982), while others suggest BI cattle have shown an advantage in DP (Black et al., 1934; Butler et al., 1956a; Butler et al., 1956b), and some report no difference between cattle sub-species (Reichhardt et al., 2023). Black et al. (1934) reported that BI × BT steers had DP between 2-4% greater than BT steers. Lunt et al. (1985) reported a numeric difference in DP between Angus (62.8%) and Brahman steers (64.0%). In the present study, observations were consistent with those of Black et al. (1934) and Lunt et al. (1985); BI steers had a DP approximately 4% greater than BT steers, with an average DP of approximately 64% and 62% for BI and BT steers, respectively. Differences in digestive tract size and hide thickness between BI and BT steers offer plausible explanations for differences in DP between sub-species, as BI steers have been observed to have smaller digestive tracts relative to BT steers (Black et al., 1934). Furthermore, DP may not only be influenced by cattle breed, diet, and gut fill, but also by animal age in terms of proximity to mature BW (Coyne et al., 2019). Lunstra and Cundiff (2003) reported that Angus cattle mature at a faster rate than Brahman cattle. Therefore, in the present study, BT steers may have been harvested closer to mature body weight than BI steers. In general, as cattle age and reach mature body weight DP decreases due to the growth of non-carcass components which could logically influence differences in the DP of BT and BI steers in the present study.

Gas Flux

With increased pressure on ruminant livestock industries to decrease CH_4 emissions, there is a need for continual review of available data to guide future research, policy, and mitigation strategy adoption (Beauchemin et al., 2022). In an assessment of global ruminant CH_4 emissions measurements, it was observed that the majority of cattle studies have assessed cattle of BT origin, with only 12% of cattle assessed being of BI origin (Della Rosa et al., 2022). However, BI cattle represent more than half the global cattle population and are the predominant cattle sub-species in tropical and subtropical climatic regions of the world (Utsunomiya et al. 2019). Additionally, given their global prominence, greater understanding of CH_4 emissions from BI cattle fed concentrate-based finishing rations could provide valuable insights into emission mitigation potential of sustainable intensification (FAO, 2023). Given the genomic, phenotypic, and behavioral differences between BT and BI cattle, it is logical to postulate that there may be differences in CH_4 emissions, which is important to elucidate given the reliance on prediction equations used to estimate emissions. In the nexus between pressure to report progress on climate goals and a lack of representative data of cattle of different sub-species, a need exists to collect gas flux measurements that can be used to evaluate and improve GHG emissions inventories and aid in more accurately representing the contribution of CH_4 at a global and national scale from beef cattle (Della Rosa et al., 2022).

In the present study, CH_4 emissions differed by sub-species, with BT steers producing approximately 9% more CH_4 (g/d) than BI steers; while GPT+ tended to emit more CH_4 (g/d), than GPT-. Although BI GPT- steers had fewer total visits than other treatments, all steers included in the gas flux analysis met the minimum visitation threshold described by Beck et al. (2024). Nonetheless, fewer BI GPT- steers achieved this threshold compared to other treatment groups. To the authors' knowledge, previous literature provides guidance only for determining minimum visitation thresholds using the AHCS, and methodologies have not yet been established for defining a minimum number of animals required to accurately represent a population. Future research is therefore needed to evaluate the minimum animal sample size necessary to ensure reliable treatment averages when using the AHCS.

In an evaluation of 3 experiments, Vargas et al. (2024) reported that individual CH_4 emissions ranged from 150 to 171 g CH_4/d, similar to the present study, where CH_4 emissions ranged from 145 to 165 g CH_4/d. However, despite similarities in gas flux measurement methodologies and data management between the present study and Vargas et al. (2024), only BT steers were used in the 3 experiments reported by Vargas et al. (2024), whereas the present study also utilized BI and BT steers. Many factors influence CH_4 emissions include such as the level of feed intake, type and quality of carbohydrates in the diet, feed processing, additives (*e.g.*, lipids, ionophore antibiotics), and alterations in the ruminal microflora (*e.g.*, defaunation) (Johnson and Johnson, 1995; Hristov et al., 2013; Beauchemin et al., 2022), prompting a need for further investigation in regard to these two cattle sub-species. To the authors' knowledge, this is the first study to evaluate gas flux in winter conditions of a temperate US climatic region for this combination of cattle sub-species and management strategies. In addition, future comparative CH_4 evaluations of BI and BT cattle may consider investigation of the rumen microbial community and rate and extent of carbohydrate digestion to isolate factors influencing CH_4 production differences between cattle sub-species beyond feed intake in order to identify potential interventions and mitigation opportunities.

A complexity that exists in the realm of sustainability science when applied to animal agriculture regarding gas flux measurement is the interpretation of absolute gas production versus gas production yield and intensity (Beauchemin et al., 2022). This complexity is related to the assessment of tradeoffs across the domains of sustainability to consider aspects of food security, economic viability, and social well-being (Place, 2024). Beyond enteric CH_4 emissions from beef cattle being an environmental sustainability concern, these emissions are also problematic with respect to energy utilization efficiency (Chaokaur et al., 2015). According to Johnson and Johnson (1995), cattle typically emit between 2-12% of their gross energy intake (GEI) as eructated CH_4. National inventories for enteric CH_4 are calculated in accordance with the Intergovernmental Panel on Climate Change (IPCC) guidelines, where the CH_4 conversion factor, also known as Y_m, is a critical metric used to assess the potential extent of global warming and to estimate total enteric CH_4 emissions (Houghton et al., 1996; Steinfeld et al., 2006; Gerber et al., 2013). The IPCC guidelines for a Tier 2 approach sets a default Y_m of 3 ± 1% for feedlot cattle fed stem-flaked corn in North America, a value generated predominately utilizing BT gas flux measurements (IPCC, 2006). In the present study, Y_m ranged from 4.3% to 6.1%, with BI steers having approximately 29% greater Y_m when compared to BT steers. The present study would suggest that when 3 ± 1% Y_m is used in accordance with IPCC Tier 2 guidelines to represent emissions from beef cattle fed a concentrate-based diet during the finishing phase of production, emissions would be underestimated for this population of cattle based on observed Y_m. Moreover, the present study observed that when considering MY, BI steers had approximately 19% greater MY than that of BT. When CH_4 was expressed as the mass of CH_4 emitted per unit ADG, BT steers emitted less CH_4, but the impact of managing steers with GTP resulted in a greater magnitude of difference in EI between GPT- and GPT+ for BI steers compared to BT steers. For BI steers, forgoing the use of GPT resulted in 66% greater EI, whereas for BT steers, this difference was 20%.

According to the IPCC (2019) some factors influencing efficiency of CH_4 emissions include feed digestibility, breed, level of intake, kinetics of feed passage, rumen volume, rumen fermentation profile, and/or the inclusion of other rumen microbial modifiers. When specifically considering the observed Y_m of the present study, differences between sub-species could be due to the influence of level of feed intake on the kinetics of feed passage through the rumen. As observed, BT steers consumed more feed than BI steers, and when level of feed intake increases, passage rate increases at the sacrament of feed digestibility. Therefore, BT steers are still consuming more total feed which is related to absolute (total) CH_4 emissions, but as passage rate increases less hydrogen is available per unit of intake for CH_4 production, thus reducing CH_4 emitted as a proportion of gross energy intake. Additionally, observed MY supports potential differences in passage rate influenced by differences in feed intake between cattle sub-species. Moreover, observed EI is reasonable considering greater growth rates observed for BT steers compared to BI steers, which could result in the dilution of maintenance energy requirements, meaning a greater proportion of feed energy could have been directed towards growth rather than maintenance for BT steers. The concept of dilution of maintenance and the relation to environmental sustainability of the US beef industry is further discussed in Capper and Bauman (2013).

CONCLUSION

The purpose of this study was to evaluate the growth performance, carcass characteristics, and gas flux of BT and BI steers managed with and without the use of GPT in winter conditions of a temperate climate. From a growth performance perspective, despite BI steers starting the trial at heavier IBW, BT steers consumed more feed with greater efficiency resulting in faster rates of growth allowing BT steers to finish at heavier FBW when compared to BI steers. Moreover, GPT increased DMI and G:F, resulting in greater ADG, leading to heavier FBW. Additionally, observations demonstrated that the effect of GPT differed by sub-species for DMI, G:F, HCW, and marbling score. Furthermore, BI steers had carcasses with less FT and calculated YG, but BT steers produced greater quality carcasses which was evident by greater marbling score, highlighting a limitation of BI steers in a consumer demand-driven industry. For gas flux, BI steers emitted less absolute CH_4 than BT steers; however, BT steers demonstrated lower CH_4 emissions yield and intensity. Observations highlight the ability for GPT to improve feed utilization efficiency, thus reducing GHG emissions when expressed per unit of DMI and ADG.

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Table 3.1. Descriptive statistics of environmental variables measured during the 180 d feeding period.

Month	Environmental Variable[1]														
	T_a			RH			SR			WS			P		
	Min[2]	Max[2]	Mean	Min[2]	Max[2]	Mean	Min[2]	Max[2]	Mean	Min[2]	Max[2]	Mean	Min[2]	Max[2]	Mean
OCT	-11.5	28.2	5.3	8.5	96.7	62.3	0.0	682.7	130.4	0.1	3.4	1.6	0.00	1.02	0.01
NOV	-14.0	23.2	3.2	10.7	94.9	54.6	0.0	569.3	113.6	0.2	7.4	2.1	0.00	0.51	0.00
DEC	-10.4	17.6	1.2	11.5	98.6	56.8	0.0	549.5	83.3	0.1	11.5	2.7	0.00	1.52	0.01
JAN	-30.2	16.0	-4.2	15.5	94.5	61.3	0.0	559.8	102.8	0.1	10.9	2.3	0.00	1.78	0.00
FEB	-16.2	16.9	1.8	9.2	98.7	59.3	0.0	727.8	142.4	0.2	12.4	2.6	0.00	4.32	0.04
MAR	-9.7	18.8	3.7	7.9	97.5	58.9	0.0	876.8	181.4	0.1	11.1	2.6	0.00	2.03	0.03
APR	-4.3	26.3	9.8	8.3	93.0	40.9	0.0	942.3	237.9	0.4	15.4	4.0	0.00	2.54	0.01

[1]T_a= ambient air temperature, ˚C; RH = relative humidity, %; SR= solar radiation, W/m^2; WS= wind speed, m/s; P= precipitation, mm/month.

[2]Min= Minimum, Max= Maximum.

[3]Month of 180d feeding period, were OCT= October, NOV= November, DEC= December, JAN= January, FEB= February, MAR= March, and APR= April.

Table 3.2. Dietary ingredients and analyzed chemical composition of the diets.

Item[1]	Diet			
	Starter	Step 1	Step 2	Finish
Ingredient, % DM				
Steam-flaked corn	30.0	44.0	55.0	65.0
Corn silage	50.0	40.0	30.0	20.0
Distillers grains w/ solubles	13.5	9.5	8.5	7.0
Molasses-based supplement	3.3	3.3	3.3	4.0
Mineral and vitamin supplement	3.2	3.2	3.2	4.0
Chemical Composition, DM basis[2]				
DM, %	54.6	53.1	60.3	64.3
CP, %	15.7	16.2	14.2	14.4
ADF, %	11.2	9.4	8.1	7.8
NDF, %	23.3	21.2	18.6	17.2
Lignin, %	1.8	1.6	1.9	1.3
Starch, %	43.1	46.3	52.8	53.2
Ash, %	7.0	5.6	3.9	4.5
TDN, %	78.0	80.5	82.0	82.5
NE_m, Mcal/kg	1.91	1.98	2.04	2.06
NE_g, Mcal/kg	1.27	1.33	1.38	1.40
GE, Mcal/kg	4.42	4.49	4.45	4.44

[1]DM = dry matter; CP = crude protein; ADF = acid detergent fiber; NDF = neutral detergent fiber; TDN = total digestible nutrients; NE_m = net energy for maintenance; NE_g = net energy for gain; GE = gross energy.

[2]Dietary composition was determined via wet chemistry.

Table 3.3. Growth performance of finishing *Bos taurus taurus* and *Bos taurus indicus* steers managed with and without the use of growth-promoting technologies during Phase 1 (0 to 83 days).

Item[1]	*Bos taurus indicus*		*Bos taurus taurus*		SEM[3]	S[4]	T[4]	S×T[4]
	GPT-[2]	GPT+[2]	GPT-[2]	GPT+[2]				
n, pen	5	5	5	5	-	-	-	-
IBW, kg	364	364	323	322	8.5	<0.01	0.98	1.00
FBW, kg	417	429	502	521	3.9	<0.01	0.02	0.23
ADG, kg	0.88	1.02	1.88	2.11	0.046	<0.01	0.01	0.24
DMI, kg/d	7.1	6.8	9.9	9.6	0.14	<0.01	0.19	0.64
DMI_{BW}, % of BW	1.86	1.78	2.38	2.24	0.037	<0.01	0.09	0.35
G:F	0.125	0.149	0.191	0.223	0.0071	<0.01	<0.01	0.38

[1]IBW = initial body weight; FBW = final body weight; ADG = average daily gain; DMI = dry matter intake; DMI_{BW} = dry matter intake according to the body weight; G:F = gain to feed ratio.

[2]Experimental management treatment; GPT-= managed without the use of growth-promoting technologies, GPT+= cattle managed with the use of growth-promoting technologies.

[3]SEM= standard error of the mean.

[4]S = main effect cattle sub-species; T = main effect management treatment; S×T = interaction between cattle sub-species and management treatment.

Table 3.4. Growth performance of finishing *Bos taurus taurus* and *Bos taurus indicus* steers managed with and without growth-promoting technologies during Phase 2 (84 to 180 days).

Item[1]	*Bos taurus indicus*		*Bos taurus taurus*		SEM[3]	S[4]	T[4]	S×T[4]
	GPT-[2]	GPT+[2]	GPT-[2]	GPT+[2]				
n, animal	50	50	46	46	-	-	-	-
IBW, kg	441	453	477	497	4.8	<0.01	<0.01	0.37
FBW, kg	538	583	603	637	4.2	<0.01	<0.01	0.14
ADG, kg	0.74	1.22	1.42	1.78	0.044	<0.01	<0.01	0.14
DMI, kg/d	7.2[c]	8.0[b]	11.2[a]	11.3[a]	0.18	<0.01	<0.01	0.04
DMI_{BW}, % BW	1.43[b]	1.53[b]	2.08[a]	2.03[a]	0.029	<0.01	0.43	<0.01
G:F	0.101[c]	0.152[a]	0.127[b]	0.157[a]	0.0042	<0.01	<0.01	<0.01

[1]IBW = initial body weight; FBW = final body weight; ADG = average daily gain; DMI = dry matter intake; DMI_{BW} = dry matter intake according to the body weight; G:F = gain to feed ratio.

[2]Experimental management treatment; GPT-= managed without the use of growth-promoting technologies, GPT+= cattle managed with the use of growth-promoting technologies.

[3]SEM= standard error of the mean.

[4]S = main effect cattle sub-species; T = main effect management treatment; S×T = interaction between cattle sub-species and management treatment.

[a,b,c] Means in the same row within main effect that do not have a common superscript letter differ, $P \leq 0.05$.

Table 3.5. Carcass data from *Bos taurus taurus* and *Bos taurus indicus* steers managed with and without the use of growth-promoting technologies following a 180 day feeding period.

Item[1]	*Bos taurus indicus*		*Bos taurus taurus*		SEM[3]	S[4]	T[4]	S×T[4]
	GPT-[2]	GPT+[2]	GPT-[2]	GPT+[2]				
n, animal	49	49	46	46	-	-	-	-
HCW, kg	345[c]	376[b]	373[b]	390[a]	3.2	<0.01	<0.01	0.02
DP, %	64.1	64.4	61.8	61.2	0.28	<0.01	0.89	0.07
FT, cm	1.22	1.11	1.56	1.38	0.061	<0.01	0.14	0.57
LMA, cm^2	85.2	92.0	79.7	84.9	1.33	<0.01	<0.01	0.42
Calculated YG	2.78	2.59	3.62	3.34	0.096	<0.01	0.11	0.63
Marbling Score[5]	382[c]	380[c]	552[a]	500[b]	15.1	<0.01	0.09	0.03
Liver Abscess Prevalence,[6] %								
0	85.7	71.4	67.4	73.9	6.91	0.21	0.50	0.08
A-	4.1	6.1	6.5	8.7	4.15	0.48	0.55	0.92
A	0.0	4.1	2.2	2.2	2.83	0.95	0.30	0.19
A+	10.2	18.4	23.9	15.2	6.29	0.33	1.00	0.12
Total Abscess Prevalence	14.3	28.6	32.6	26.1	6.91	0.21	0.50	0.08

[1]HCW = hot carcass weight; DP = dressing percentage; FT = Back fat measured between the 12th and 13th rib after 24 h chill; LMA = longissimus muscle area; YG = yield grade.
[2]Experimental management treatment; GPT-= managed without the use of growth-promoting technology, GPT+= cattle managed with the use of growth-promoting technology.
[3]SEM= standard error of the mean.
[4]S = main effect cattle sub-species; T = main effect management treatment; S×T = interaction between cattle sub-species and management treatment.
[5]Marbling score scale: 300 = slight, 400 = small, 500 = modest.
[6]0 = non-abscessed liver; A-minus (A-)= one or two small abscesses; A = two to four small, active abscesses; A-plus (A+)=one or more large, active abscesses, including any open and adhered abscesses.
[a,b,c]Means in the same row within main effect that do not have a common superscript letter differ, $P \leq 0.05$.

Table 3.6. United State Department of Agriculture yield and quality grade distribution for *Bos taurus taurus* and *Bos taurus indicus* steers managed with and without the use of growth-promoting technologies following a 180 day feeding period.

Item[1]	*Bos taurus indicus*		*Bos taurus taurus*		SEM[3]	S[4]	T[4]	S×T[4]
	GPT-[2]	GPT+[2]	GPT-[2]	GPT+[2]				
n, animal	49	49	46	46	-	-	-	-
USDA YG, %								
YG 1	16.3	16.3	0.0	0.0	5.28	<0.01	1.00	1.00
YG 2	57.1	44.9	4.4	8.7	7.02	<0.01	0.47	0.20
YG 3	20.4	32.7	52.2	67.4	7.37	<0.01	0.04	0.99
YG 4	4.1	0.0	43.5	23.9	7.31	<0.01	0.02	0.25
No Roll	2.0	6.1	0.0	0.0	3.42	0.02	0.30	1.00
USDA QG, %								
Prime	0.0	0.0	6.5	4.4	3.64	<0.01	0.64	1.00
Choice	28.6	28.6	93.5	95.7	6.45	<0.01	0.84	0.68
Select	59.2	63.3	0.0	0.0	7.02	<0.01	0.68	1.00
No Roll	12.2	8.2	0.0	0.0	4.68	<0.01	0.50	1.00

[1]USDA Yield Grade (YG); USDA Quality Grade (QG), Quality grade marketing category determined by expert marbling score: USDA Prime = Slightly Abundant^{0} to Abundant^{99}; USDA Choice = Small^{0} to Moderate^{99}; USDA Select = Slight^{0} to Slight^{99}, No Roll = Carcass was not designated an official USDA QG due to intramuscular fat classification lower than USDA Select.
[2]Experimental management treatment; GPT-= managed without the use of growth-promoting technology, GPT+= cattle managed with the use of growth-promoting technology.
[3]SEM= standard error of the mean.
[4]S = main effect cattle sub-species; T = main effect management treatment; S×T = interaction between cattle sub-species and management treatment.

Table 3.7. Gas flux of finishing *Bos taurus taurus* and *Bos taurus indicus* steers managed with and without the use of growth-promoting technologies during Phase 2 (84 to 180 days).

Item[1]	*Bos taurus indicus*		*Bos taurus taurus*		SEM[3]	S[4]	T[4]	S×T[4]
	GPT-[2]	GPT+[2]	GPT-[2]	GPT+[2]				
n, animal	28	37	40	44	-	-	-	-
AHCS visits, n	71	148	109	151	-	-	-	-
DMI, kg/d	7.3[c]	8.1[b]	11.1[a]	11.4[a]	0.22	<0.01	0.03	0.04
ADG, kg	0.73	1.20	1.43	1.81	0.057	<0.01	<0.01	0.31
CH_4, g/d	145	153	162	165	5.8	<0.01	0.09	0.67
CO_2, g/d	8000	7788	10051	10174	165.0	<0.01	0.42	0.21
O_2, g/d	5504[c]	5598[c]	6743[b]	7077[a]	109.0	<0.01	<0.01	0.01
H_2, g/d	1.06	1.09	1.26	1.09	0.076	<0.01	0.26	0.09
Y_m, % GEI	6.07	5.65	4.30	4.43	0.193	<0.01	0.63	0.08
MY, g CH_4/kg DMI	20.2	18.8	14.4	14.8	0.63	<0.01	0.61	0.08
EI, g CH_4/kg ADG	244.8[a]	124.5[b]	121.0[b]	98.9[b]	17.5	<0.01	<0.01	<0.01

[1]AHCS = automated head chamber system; DMI = dry matter intake; ADG = average daily gain; CH_4 = methane; CO_2 = carbon dioxide; O_2 = oxygen; H_2 = hydrogen; Y_m= CH_4 emitted as a percent of gross energy intake (GEI); MY = methane yield; EI = emissions intensity.
[2]Experimental management treatment; GPT-= managed without the use of growth-promoting technology, GPT+= cattle managed with the use of growth-promoting technology.
[3]SEM= standard error of the mean.
[4]S = main effect cattle sub-species; T = main effect management treatment; S×T = interaction between cattle sub-species and management treatment.
[a,b,c]Means in the same row within main effect that do not have a common superscript letter differ, $P \leq 0.05$.

CHAPTER 4- EVALUATION OF PREDICTION MODEL ACCURACY AND AGGREGATION TO ESTIMATE METHANE EMISSIONS OF FINISHING BEEF STEERS

INTRODUCTION

Globally, more than 150 countries and interested parties have signed the Global CH_4 Pledge to take voluntary actions to contribute to a collective global CH_4 reduction of 30% from 2020 levels by 2030 (GMP, 2025). Since CH_4 is a short-lived greenhouse gas (GHG), reductions are viewed as an effective means of limiting global warming (Beauchemin et al., 2022). In 2022, CH_4 contributed 276.8 MMT CO_2 eq to total United States (U.S.) agriculture sector emissions, with enteric fermentation accounting for approximately 32.5% of those emissions (EPA, 2024). As of 2022, cattle remained the primary source of CH_4 emissions from enteric fermentation in the U.S., with beef cattle contributing 137 MMT CO_2 eq, representing over 71% of total enteric fermentation emissions (EPA, 2024). Despite this substantial source of emission for the agriculture sector, the ability for many enteric CH_4 prediction models to accurately estimate enteric CH_4 production under diverse commercial conditions is limited (NASEM, 2016; Vargas et al., 2025). Furthermore, direct measurement of CH_4 production requires complex equipment, substantial capital investment, and is generally impractical in commercial production settings (Kebreab et al., 2008). Therefore, the development and application of enteric CH_4 prediction models represents an important and practical alternative for CH_4 estimation (Kebreab et al., 2008).

The ability to accurately estimate CH_4 emissions can improve the identification of efficiency differences among cattle, support the adoption of sustainable production practices via enhanced quantification of emissions reduction potential and associated return on investment, inform sector-specific mitigation strategies, strengthen measurement, reporting, and verification

(MRV) programs, and guide regulatory policy development (Vargas et al., 2025). Enteric CH_4 prediction models are mathematical representations used to estimate CH_4 emissions from enteric fermentation based on empirical relationships of underlying biological processes, and at present are used at a national and global level (Kebreab et al., 2008). These models can serve as an indispensable tool for researchers and policy makers to convey scientific knowledge, innovate new solutions, and re-evaluate established assumptions (Tedeschi, 2006).

Recent observations by Vargas et al. (2025) reported limited predictive accuracy of 72 enteric CH_4 models when applied to 446 finishing steers across 5 finishing experiments when cattle were fed a concentrate-based diet. Observations reported by Vargas et al. (2025) highlight the need for continued efforts to improve model accuracy to enhance the estimation of GHG contributions from beef cattle production systems. In response to the considerable variability resulting from the use of a single enteric CH_4 prediction model (Vargas et al., 2025), the Beef Cattle Nutrient Requirements Model employs multiple predictive models, conditionally aggregated based on dietary forage proportion, to generate CH_4 estimates (NASEM, 2016). To the authors' knowledge, an evaluation comparing observed CH_4 emissions with estimates generated from various aggregations of enteric CH_4 prediction models has not been conducted in finishing beef cattle fed concentrate-based diets to determine whether aggregation methodologies improve estimation accuracy. Consistent with the approach of the Beef Cattle Nutrient Requirements Model, which utilizes multiple prediction models, the objective of this study was to evaluate the accuracy and precision of enteric CH_4 estimates generated from different enteric CH_4 predictive model aggregations relative to observed emissions in finishing beef steers fed a concentrate-based diet. The authors' hypothesized that aggregating enteric CH_4 prediction models would improve the accuracy of estimating CH_4 emissions from finishing beef steers, due to the substantial variation in estimation accuracy amongst existing prediction models when utilized singularly (Vargas et al., 2025).

MATERIALS AND METHODS

An independent database was constructed utilizing data from seven experiments conducted at the Colorado State University Agricultural Research, Education, and Development Center experiment station in Fort Collins, CO, from March 2023 to October 2025. All procedures involving animals were approved by the Colorado State University Institutional Animal Care and Use Committee (experiment 1: protocol no. 4072, experiment 2: protocol no. 3712, experiment 3: protocol no. 4689, experiment 4: protocol no. 4689, experiment 5: protocol no. 5924, experiment 6: protocol no. 5403, experiment 7: protocol no. 6460).

Animals and Experiment Description

The independent database utilized in this study was comprised of individual animal growth performance and CH_4 production data from 7 experiments, yielding individual data on 888 finishing steers. For experiment 1, 166 yearling *Bos taurus* steers (initial body weight [IBW] = 498 ± 38 kg) were fed for 69 d. In experiment 2, 299 yearling steers (133 *Bos indicus*, 166 *Bos taurus*, IBW= 470 ± 48) were on feed for 96 d. Experiment 3 consisted of 51 *Bos taurus* steers that were fed for 52 d (*n*= 21, IBW= 553 ± 16) and 80 d (*n*= 30, IBW= 502 ± 14). For experiment 4, 36 yearling *Bos taurus* steers were fed for 76 d. Experiment 5 utilized 82 yearling *Bos taurus* steers (IBW= 552 ± 37) fed for 53 d and 55 yearling *Bos taurus* steers (IBW= 495 ± 35) fed for 76 d. In experiment 6, 26 yearling *Bos taurus* steers (IBW= 602 ± 53) were on feed for 49 d. Lastly, experiment 7 consisted of 173 *Bos taurus* steers (IBW= 460 ± 52) on feed for 115 d.

For all experiments, cattle were housed in a Climate Smart Research Pen (15 m × 43 m), capable of housing 50 steers/pen, where the experimental unit was considered the individual animal. Each Climate Smart Research Pen was equipped with one GreenFeed automated head chamber system (AHCS, C-Lock, Rapid City, SD, USA), five SmartFeed bunk systems (C-Lock, Rapid City, SD, USA), two automatic waterers, a concrete bunk pad (15 m × 3 m), and a metal roof (15 m × 3 m) covering the SmartFeed bunk systems, AHCS, and approximately 7% of the pen surface. Steers were monitored daily by trained personnel who evaluated fresh feed and water allocation, cattle health, locomotion, and clinical signs of disease. When the experiments were initiated, all cattle received a radio frequency identification tag (Allflex, USA Inc., Dallas, TX, USA) placed in the animal's left ear.

Methane Measurement

Each Climate Smart Research Pen contained one AHCS for the collection of gas flux (*i.e.*, CH_4, CO_2, and H_2 emissions, and O_2 consumption). Steers were exposed to the AHCS during an acclimation period of at least 7 d before the initiation of data collection. During the acclimation period, the headbox extension panels (*i.e.*, wings) were placed on the AHCS and cattle panels were used to create an alley in front of the AHCS to ensure only one animal at a time had access to the AHCS. Measurements collected during the acclimation period were not included in the data analysis. Throughout the study, steers were allowed to visit the AHCS system up to 6 visits/d, with a minimum of 4 h between each visit. The AHCS was programmed to allow consumption of up to 6 drops of alfalfa pellets per visit (average 36 g as fed/drop, 93% DM), with drops occurring every 30 s while a steer was utilizing the AHCS. These configuration settings encouraged an even distribution of AHCS visits for each steer throughout the day, capturing the diurnal variation in gas flux, and ensuring each steer remained at the AHCS for a minimum duration of 2 min during gas flux sample collection (Vargas et al., 2024).

To ensure proper functioning and performance of the AHCS, CO_2 recovery tests were performed at the beginning, end, and every 28 d throughout the experimental period to gravimetrically calibrate the AHCS. Additionally, zero and span calibrations of the CH_4, CO_2, H_2, and O_2 gas analyzers were performed every 3 d via an autocalibration system located onboard the AHCS. Raw data collected was validated by the AHCS manufacturer, which included checking head proximity, visit length, and airflow, as well as providing corrections for wind. Steers utilized in the independent database were required to meet the minimum criteria of 55 “good” AHCS visits (Vargas et al., 2024). A “good” visit required visit duration was between 2 and 8 min and the airflow to be greater than or equal to 26 L/s (Arthur et al., 2017; Gunter and Beck, 2018). For the 888 steers included in the database, the average number of gas flux visits per animal by experiment was as follows; experiment 1: 177 visits, experiment 2: 138 visits, experiment 3: 104 visits, experiment 4: 158 visits, experiment 5: 101 visits, experiment 6: 72 visits, experiment 7: 197 visits.

Diet, Feed Management, and Intake Measurement

During the experimental period, all steers were fed a finishing diet that was comprised of three primary commodities: steam-flaked corn, corn silage, and dried distillers grains with solubles (DDGS; Table 4.1). Dietary nutrient composition reported was determined via wet chemistry and supplemented, when lacking wet chemistry analyses, utilizing the Beef Cattle Nutrient Requirements Model (Table 4.2). Across all experiments feed samples were collected weekly throughout the respective experimental period, dried at 65 °C for a minimum of 48 h to determine analytic dry matter (DM). After the completion of each experimental period, feed samples were composited and analyzed at a commercial laboratory using a wet chemistry package (Dairy One, Ithaca, NY, USA). For experiment 5, lignin, non-fiber carbohydrates, ether extract, and ash were simulated using the National Academies of Science, Engineering, and Medicine Beef Cattle Nutrient Requirements Model 2016 (v.1.0.37.21). For all experiments, sugar was simulated using the National Academies of Science, Engineering, and Medicine Beef Cattle Nutrient Requirements Model 2016 (v.1.0.37.21).

In the Climate Smart Research Pens individual animal feed intake was determined utilizing SmartFeed bunk systems, and ad libitum bunk management was utilized to manage feed delivery across all experiments. All cattle underwent at least a 7 d acclimation period to the SmartFeed bunk systems before the initiation of data collection. Feed intake data collected during the acclimation period were not used in the data analysis. The SmartFeed bunk systems were calibrated at the beginning and end of the experimental period and every 7 d during the experimental period. Following the conclusion of the experimental period, raw feeding events were downloaded from the manufacturer's online software. Feeding events that were flagged by the manufacturer (e.g., unallocated feed or nonsensical eating rate), exceeded 3600 s in duration, and/or were greater than 10 kg mass difference were omitted from determination of daily feed intake. Feeding events were then summed by day to determine daily as-fed feed finishing diet intake. As-fed feed finishing diet intake was converted to dry matter intake (DMI) by multiplying by the percent DM of the finishing diet. To determine total daily DMI, daily finishing diet DMI was summed with daily alfalfa pellet drops from the AHCS.

Growth Performance Measurement

Steers in each experiment were individually weighed using a hydraulic squeeze chute (Model no. SHEW10497, Silencer, Moly Manufacturing Inc., Lorraine, KS, USA) equipped with an electronic weighing system (ID5000, Tru-Test Inc., Mineral Wells, TX, USA) on two consecutive days at the beginning of the experiment (d −1 and 0) to determine IBW and at the end of the experimental period to determine final BW (FBW). Body weight (BW) data collected were reduced by 4% using Equation 1 to account for digestive tract fill (NASEM, 2016).

Equation 1:

$$BW, shrunk, kg = BW * 0.96$$

Experimental mid-point BW (MBW) was calculated by taking the average of IBW and FBW, using Equation 2.

Equation 2:

$$MBW, kg = (FBW + IBW)/2$$

Average daily gain (ADG) was calculated by subtracting IBW from FBW and then dividing by days on feed (DOF) (*i.e.*, the duration of the experimental period), using Equation 3.

Equation 3:

$$ADG, {}^{kg}/_{d} = (FBW - IBW)/DOF$$

Feed efficiency, gain to feed ratio (G:F), was determined by dividing average daily gain by DMI using Equation 4.

Equation 4:

$$G{:}F, {}^{kg}/_{kg} = ADG/DMI$$

Database Stratification

Due to differences in cattle type, the independent database created for the purposes of this study was designated into three strata for evaluation. The strata included 1) analysis of the entire database containing 888 individual animal records, 2) analysis of the *Bos taurus* steers only, containing 755 individual animal records; excluding *Bos indicus* steers, and 3) analysis of the *Bos indicus* steers only, containing 133 individual animal records; excluding the *Bos taurus* steers.

Enteric CH_4 Prediction Models

In this study, 66 enteric CH_4 prediction models, linear and non-linear, developed for the estimation of CH_4 emissions (MJ/d) from beef cattle were retrieved from the literature (Table 4.3). Selection criteria for models retrieved from the literature required that CH_4 prediction equations be developed for beef cattle and compatible with the input variables in the independent database. When applicable and specified, equations were further restricted to steers consuming a concentrate-based, low-forage finishing diet.

Enteric CH_4 Prediction Model Evaluation

Enteric CH_4 prediction models were evaluated with R (R Core Team, 2021, v. 4.4.1) software using the lmer() function within the lme4 package to construct a linear mixed-effects model. During model evaluation, the mean square prediction error (MSPE, MJ^2/d^2) was calculated using Equation 5.

Equation 5:

$$MSPE = \sum_{i=1}^{n} (Oi - Pi)^2 / n$$

Where Oi is the observed value and Pi is the predicted value.

The root of the MSPE (RMSPE), expressed in MJ/d and as a percentage of the observed mean, was calculated to estimate overall predicted error as described by Vargas et al. (2025), using Equation 6.

Equation 6:

$$RMSPE = \sqrt{MSPE}$$

The RMSPE was then decomposed into mean bias (MB), slope bias (SB), and residual bias (RB; Tedeschi, 2006). As described by Tedeschi (2006), MB represents error that is attributable to overall bias, SB reflects error due to deviation of the regression slope from unity, and RB represents random error. Additionally, the concordance correlation coefficient (CCC) was calculated as described by (Lin, 1989), using Equation 7.

Equation 7:

$$CCC = P \times Cb$$

Where P is the Pearson correlation coefficient and Cb is the bias correction factor. The P accounts for model precision by measuring the strength of the linear association between observed and predicted values, whereas the Cb measures the extent to which predicted values deviate from the line of equality, accounting for model accuracy. The CCC classification scale from Proctor et al. (2024) was implemented in the present study, where values of CCC for no agreement were classified as < 0, slight agreement as 0 to 0.39, moderate agreement as 0.40 to 0.59, adequate agreement as 0.60 to 0.80, and excellent agreement as > 0.80. In addition to formal model evaluation, Pearson correlation coefficients were calculated in R (R Core Team, 2021, v. 4.4.1) to evaluate linear associations between enteric CH_4 production and growth performance and dietary nutrient composition variables. Correlation matrices and corresponding p-values were generated using the rcorr() function from the Hmisc package. Statistical significance was declared at $P \leq 0.05$.

Enteric CH_4 Prediction Model Ranking and Aggregation

All enteric CH_4 prediction models were allocated a weighted rank based equally on CCC and RMSPE, utilizing methodologies discussed by Tedeschi (2006). Following designation of enteric CH_4 prediction model rank, seven enteric CH_4 prediction model aggregations were generated based on model rank. Regarding the seven enteric CH_4 prediction aggregations, this study focused on primarily generating aggregations with fewer than 9 models, as the Beef Cattle Nutrient Requirements Model uses between 2-9 models to estimate CH_4 emissions. For example, a low-forage diet (≤ 20% dietary DM) aggregates 5 models to predict emissions from beef cattle (NASEM, 2016). The Beef Cattle Nutrient Requirements Model was included as a control aggregation in the present study.

Model Aggregation Evaluation

Overall performance of model aggregations developed were evaluated with R (R Core Team, 2021, v. 4.4.1) software using the lmer() function within the lme4 package to construct a linear mixed-effects model. The CCC, RMSPE, MB, SB, and RB were calculated using methodologies previously described. Additional analysis was conducted to evaluate predicted versus observed enteric CH_4 emissions by aggregation methodology. A linear-mixed effects model was constructed with R (R Core Team, 2021, v. 4.4.1) software using the lmer() function within the lme4 package. The fitted model was:

$$Y_i = \mu + A_i + C_j + E_i$$

Where Y_i is the response variable; A_i is the fixed effect of the method of aggregation; C_j is the random effect of animal cohort; and E_i is the experimental error. Least-squares means were derived using the emmeans package in R (R Core Team, 2021, v. 4.4.1), with Tukey's HSD adjustment. Differences were declared significant at $P \leq 0.05$.

RESULTS

Diet, Growth Performance, and CH_4 Production Descriptive Statistics

Experimental diets were formulated using three primary commodities: steam-flaked corn, corn silage, and DDGS. Despite similar commodities being used across experiments there was variation in commodity inclusion where steam-flaked corn inclusion ranged between 51 and 65%, corn silage inclusion ranged between 19 and 27%, and DDGS inclusion ranged between 4 and 26% (Table 4.1). Dietary DM of the finishing diet across all experiments varied between 64.3 and 71.8% (Table 4.2).

When assessing the entire database containing 888 individual animal records, steer IBW ranged between 312 and 721 kg, while FBW ranged between 368 and 882 kg (Table 4.4). Moreover, DMI varied between 5.1 and 19.7 kg /d, with an average DMI of 12.0 kg across all experiments represented in the independent database. Enteric CH_4 production measured utilizing an AHCS was observed to range between 53 and 307 g CH_4/d, which equates to approximately 3 and 17 MJ CH_4/d, respectively. However, when assessing the database containing 755 individual animal records, stratified to only include *Bos taurus* steers, the same range was observed for IBW, but FBW varied between 505 and 882 kg (Table 4.5). Moreover, average DMI increased to 12.8 kg/d, ranging from 7.7 to 19.7 kg/d. Enteric CH_4 averaged 185 g/d, but was observed to vary from 115 to 307 g/d, corresponding to approximately 6 to 17 MJ/d, respectively. Furthermore, for the database containing 133 individual animal records, stratified to include *Bos indicus* steers, IBW was observed to have a smaller range, varying between 312 and 525 kg, while FBW ranged between 368 and 671 kg (Table 4.6). Average DMI decreased to 7.6 kg/d and ranged between 5.1 and 11.0 kg/d. Production of enteric CH_4 ranged from 53 to 213 g/d (approximately 3-12 MJ/d), averaging 131 g/d.

When considering the entire database, comprised of 888 individual finishing steers, enteric CH_4 production was positive and significantly associated with BW (r = 0.59), ADG (r = 0.50), DMI (r = 0.54) and G:F (r = 0.20), as well as ether extract, lignin, hemicellulose, and gross energy (Table 4.7). However, the dietary nutrient composition of crude protein (r = -0.12), ash (r = -0.14), non-fiber carbohydrates (r = -0.14), starch (r = -0.32), forage (r = -0.14), cellulose (r = -0.18), and acid detergent fiber (r = -0.14) demonstrated a negative and significant association with enteric CH_4 production. Dietary sugar, neutral detergent fiber, total digestible nutrients, digestible energy, and metabolizable energy were not observed to have a significant association with enteric CH_4 production.

Within the stratified *Bos taurus* database (*n* = 755 finishing steers), enteric CH_4 production was again positively and significantly associated with BW (r = 0.41), ADG (r = 0.27), DMI (r = 0.28), and G:F (r = 0.11; Table 4.8). Positive associations were also observed between enteric CH_4 production and dietary crude protein (r = 0.09), ether extract (r = 0.22), lignin (r = 0.23), and gross energy (r = 0.19). In contrast, several dietary variables exhibited significant negative associations with enteric CH_4 production, including non-fiber carbohydrates (r = -0.15), sugar (r = -0.22), starch (r = -0.20), forage (r = -0.29), cellulose (r = -0.28), neutral detergent fiber (r = -0.13) and acid detergent fiber (r = -0.23). No significant associations were detected between enteric CH_4 production and dietary ash, hemicellulose, total digestible nutrients, digestible energy, or metabolizable energy. Relative to the entire database, similar positive associations with CH_4 were observed for BW, ADG, DMI, G:F, ether extract, and gross energy, whereas significant and negative associations were consistent for non-fiber carbohydrates, starch, forage, acid detergent fiber, and cellulose. Total digestible nutrients, digestible energy, and metabolizable energy were not significantly associated with CH_4 in either database. In contrast, associations between CH_4 and crude protein, ash, sugar, and hemicellulose varied in a database dependent manner. Within the stratified *Bos indicus* database (n = 133 finishing steers), enteric CH_4 production was positively and significantly associated with BW (r = 0.39), ADG (r = 0.20), and DMI (r = 0.43; Table 4.9). Positive associations were also observed between enteric CH_4 production and dietary neutral detergent fiber (r = 0.42) and hemicellulose (r = 0.42). Conversely, several dietary variables demonstrated significant negative associations with enteric CH_4 production, including ash (r = -0.27), non-fiber carbohydrates (r = -0.39), starch (r = -0.19), lignin (r = -0.30), cellulose (r = -0.26), and acid detergent fiber (r = -0.40). No significant associations were observed between enteric CH_4 production and G:F, crude protein, ether extract, sugar, forage, total digestible nutrients, or gross, digestible, and metabolizable energy. When compared to the entire database, similar positive and significant associations were observed for BW, ADG, DMI, and NDF; while similar negative and significant associations were reported for ash, non-fiber carbohydrates, starch, acid detergent fiber, and cellulose. Conversely, G:F and gross energy were also positively and significantly associated with CH_4 in the entire database, but not significant in the stratified *Bos indicus* database.

Model Evaluation

The ability for the 66 selected models to estimate enteric CH_4 observed in an independent database containing 888 individual animal records, varied as evident by RMSPE and CCC metrics (Figure 4.1). Of the 66 models evaluated, 46 models underestimated observed CH_4, while 20 models overestimated observed CH_4 (Figure 4.2). Model 61 (Ellis et al., 2007; Equation 9b) had the greatest CCC (CCC = 0.63) and smallest RMSPE (RMSPE = 1.57 MJ/d), utilizing metabolizable energy intake and dietary forage proportion as predictors to estimate enteric CH_4 emissions from beef steers (Table 4.10). Additionally, model 14 (van Lingen et al., 2019; Equation 24) utilized gross energy intake and demonstrated to achieve a comparable CCC (CCC = 0.62) when compared to model 61. Model 59 (Ellis et al., 2007; Equation 7b) and model 60 (Ellis et al., 2007; Equation 8b) demonstrated a similarly small RMSPE to model 61 of 1.59 MJ/d with a CCC of 0.56 and 0.58, respectively. While both models 59 and 60 utilize MEI as predictors to estimate enteric CH_4 emissions from finishing beef steers, model 59 also utilized neutral detergent fiber intake, whereas model 60 utilized acid detergent fiber intake. Additionally, model 3 (IPCC, 2019; Tier 1 Equation) achieved the smallest MB (MB = 0.17%) utilizing a standardized emissions factor and excluding the requirement of animal growth performance or dietary inputs; however, model 3 reported a CCC of 0.00. When examining RB, models 61, 59, and 60 were observed to have a greater proportion of random error compared to errors associated with MB or SB. Furthermore, model 65, 52, 45, and 2 (IPCC, 2019; Tier 2) yielded a SB of approximately 0.0% (*i.e.*, essentially no error due to deviation of the regression slope from unity), however the MB, RMSPE, and CCC were generally poor in comparison to other models evaluated. Overall, only five models evaluated were classified to have adequate agreement with a CCC ranging from 0.60 to 0.80, according to criteria of Proctor et al. (2024). A commonality amongst models with adequate agreement included the quantification of DMI to be utilized as a predictor variable either directly or indirectly.

When evaluating the ability for the same 66 selected models to estimate enteric CH_4 observed in an independent database containing 755 individual animal records, including only *Bos taurus* steers, variation was observed in the RMSPE and CCC metrics (Figure 4.3). Of the 66 models evaluated, 43 models underestimated observed CH_4, while 23 models overestimated observed CH_4, which is consistent with previously described observations of the entire database (Figure 4.3). Model 61 (Ellis et al., 2007; Equation 9b) had the greatest CCC (CCC = 0.32), utilizing metabolizable energy intake and dietary forage proportion as predictors to estimate enteric CH_4 emissions from beef steers (Table 4.11). Notably, in comparison to the entire database where model 61 achieved a CCC of 0.63 and was similarly ranked as the top-performing model, the CCC observed in the stratified *Bos taurus* database denotes slight agreement as opposed to adequate agreement using evaluation methodologies suggested by Proctor et al. (2024). Additionally, model 14 (van Lingen et al., 2019; Equation 24) utilized gross energy intake and demonstrated to achieve a comparable CCC (CCC = 0.32) to model 61. Comparably, model 14 performed well in the evaluation of the entire database. Model 61 achieved the smallest MB of 0.37%. Model 8 (Galyean and Hales, 2022; Equation 3) also demonstrated a small and comparable MB of 0.41%, RMSPE of 2.01 MJ/d, and CCC of 0.31, using DMI and the ratio of starch to NDF as predictors to estimate enteric CH_4 emissions from finishing beef steers; however, SB was approximately 26%. Observations for model 8 in the stratified *Bos taurus* database were consistent with those from the entire database. When examining RB, model 60 (Ellis et al., 2007; Equation 8b) and model 11 (van Lingen et al., 2019; Equation 21) were observed to have a greater proportion of random error compared to errors associated with MB or SB, with RB of 98.25% and 96.16%, respectively. Model 60 and model 11 consistently ranked among the top 8 models in evaluations of both the entire and stratified *Bos taurus* databases. Furthermore, model 46 (Ellis et al., 2009; Equation U) and 32 (Ellis et al., 2009; Equation E) yielded a SB of 0.00% (*i.e.*, no error due to deviation of the regression slope from unity); however, these models had a CCC of 0.01 and 0.00, respectively. Overall, only four models evaluated had a CCC ≥ 0.30, and in general CCC demonstrated poor agreement according to criteria established by Proctor et al. (2024). A commonality amongst the four models with CCC ≥ 0.30 included the quantification of DMI to be utilized as a predictor variable either directly or indirectly, as observed for the entire database.

When evaluating the ability for the 66 selected models to estimate enteric CH_4 observed in an independent database containing 133 individual animal records, including only *Bos indicus* steers, variation was observed in the RMSPE and CCC metrics (Figure 4.5). Of the 66 models evaluated, 42 models underestimated observed CH_4, while 24 models overestimated observed CH_4 (Figure 4.6). Model 4 (Hales et al., 2022; Equation 1) had the greatest CCC (CCC = 0.51), utilizing DMI as a predictor to estimate enteric CH_4 emissions from beef steers (Table 4.12). Moreover, model 4, which exhibited a CCC of 0.40 in the entire database evaluation, indicating similar moderate agreement according to Proctor et al. (2024); however, model 4ranked 1st in the stratified *Bos indicus* database but 30th in the full database evaluation. Model 4 had the smallest RMSPE of 1.24 MJ/d, equating to approximately 17% of overall predicted error. Models 28 and 59 had a similar RMSPE when compared to model 4 of 1.29 MJ/d while having a CCC of 0.39; however, SB was 42.46% and 65.27%, respectively. Model 28 and model 59 consistently ranked among the top 5 models in evaluations of both the entire and stratified *Bos indicus* databases. Model 28 (Ellis et al., 2009; Equation A) achieved the smallest MB of 0.64% utilizing DMI as a predictor of enteric CH_4 production, while also being observed to have a CCC of 0.39 and RMSPE of 1.29 MJ/d; however, SB was 42.56%. Additionally, model 44 (Ellis et al., 2009; Equation B) was observed to have the smallest SB at 0.01% (*i.e.*, essentially no error due to deviation of the regression slope from unity), utilizing dietary hemicellulose intake; however, RMSPE and MB were 2.23 MJ/d and 67.87%, respectively. Models 11 (van Lingen et al., 2019; Equation 21) and 58 (Ellis et al., 2007; Equation 6b), had the greatest RB of 79.60% and 74.05%, respectively; nonetheless, CCC was

0.15 and 0.04, respectively. Overall, only one model (model 4; CCC = 0.51) demonstrated moderate agreement according to the classification criteria reported by Proctor et al. (2024). Dry matter intake was used as a predictor variable in estimating enteric CH_4 production in model 4, the top performing model when evaluating the stratified *Bos indicus* database. In general, the majority of models demonstrated poor agreement in estimating enteric CH_4 emissions.

Model Aggregation

Seven model aggregations were generated based on a weighted model rank utilizing CCC and RMSPE metrics for the entire database (Table 4.13), stratified; *Bos taurus* database (Table 4.14), and stratified; *Bos indicus* database (Table 4.15). When considering the entire database, utilizing 888 individual animal records, all model aggregations generated, excluding the NASEM model aggregation, achieved a CCC between 0.57 and 0.63, while MB ranged from 0.06 to 2.57% and SB varied from 0.01 to 2.02%, with > 93% of decomposed RMSPE coming from RB (Table 4.16). Excluding the NASEM model aggregation, all other model aggregations exhibited CCC values ranging from moderate to adequate agreement (CCC = 0.57-0.63), according to the classification suggested by Proctor et al. (2024), where values < 0 indicate no agreement, 0 to 0.39 slight agreement, 0.40 to 0.59 moderate agreement, 0.60 to 0.80 adequate agreement, and > 0.80 excellent agreement. Moreover, observed mean CH_4 emissions did not differ ($P > 0.05$) from the A2 (*i.e.*, aggregation utilizing the top 3 performing models), A3 (*i.e.*, aggregation utilizing the top 5 performing models), or A4 (*i.e.*, aggregation utilizing the top 9 performing models; Figure 4.7). However, observed mean CH_4 emissions differed ($P \leq 0.01$) from the prediction generated by the A1 (*i.e.*, aggregation utilizing the top performing model), A5 (*i.e.*, aggregation utilizing the top performing 25% of models), A6 (*i.e.*, aggregation utilizing the top performing 50% of models), A7 (*i.e.*, aggregation utilizing all evaluated models), and NASEM aggregations. The NASEM aggregation underpredicted CH_4 emissions significantly compared to all aggregations and the observed mean CH_4 emissions. Despite significant differences between aggregated model predictions and observed CH_4 emissions, the magnitude of prediction error was reduced. All aggregation approaches, except the NASEM aggregation, underpredicted or overpredicted CH_4 by ± 5% (Figure 4.8).

Within the stratified database of *Bos taurus* finishing steers (n = 755), all model aggregations, with the exception of the NASEM aggregation, achieved CCC values ranging from 0.25 to 0.32. According to the classification proposed by Proctor et al. (2024), these values indicate slight agreement, based on the following scale: < 0 denotes no agreement, 0 to 0.39 slight agreement, 0.40 to 0.59 moderate agreement, 0.60 to 0.80 adequate agreement, and > 0.80 excellent agreement. For model aggregations A1 through A7, MB ranged from 0.00 to 4.95%, SB ranged from 1.55 to 6.50%, and RB accounted for > 92% of the decomposed RMSPE (Table 4.17). Furthermore, observed CH_4 emissions did not differ ($P > 0.05$) from the A1, A2, A3, A4, or A5 aggregations. However, the A6, A7, and NASEM aggregations all generated estimated CH_4 emissions that were significantly ($P \leq 0.01$) less than observed emissions (Figure 4.9). The NASEM aggregation estimated enteric CH_4 emissions that were significantly ($P < 0.05$) less than all other aggregations and the observed value. Although aggregated model predictions differed significantly from observed mean enteric CH_4 emissions, the magnitude of prediction error was reduced. All aggregation approaches, except the NASEM aggregation, were within ± 5% of the observed mean (Figure 4.10).

Within the stratified database of *Bos indicus* finishing steers (n = 133), all model aggregations, with the exception of the NASEM aggregation, achieved CCC values ranging from 0.36 to 0.51. For model aggregations A1 through A7, MB ranged from 0.00 to 15.53% and RB varied from 37.31 to 61.24%. However, SB accounted for > 25% and < 45% of the decomposed RMSPE (Table 4.18). Moreover, model aggregation A2, A3, A4, A5, and A7 produced estimates for enteric CH_4 emissions that did not differ ($P > 0.05$) from the observed value (Figure 4.11). Nonetheless, A1 overpredicted ($P < 0.01$) enteric CH_4 emissions, whereas A6 and NASEM underpredicted ($P < 0.01$) enteric CH_4 emissions. The NASEM aggregation estimated enteric CH_4 emissions that were significantly ($P < 0.01$) less than all other aggregations and the observed value. Prediction discrepancies between aggregated estimates and observed mean CH_4 emissions were in some cases statistically significant; however, the magnitude of difference was reduced. All aggregation approaches, except the NASEM aggregation, were within ± 10% of the observed mean (Figure 4.12).

DISCUSSION

Enteric CH_4 prediction models are valuable tools that can be used to represent biological systems mathematically; however, they require the use of a representative sample to allow accurate and precise estimation in a different population (Vargas et al., 2025). Adding to this complexity, the production of enteric CH_4 is influenced by many factors such as animal DMI, type and quantity of carbohydrate in the diet, feed processing, addition of lipids or ionophores to the diet, alterations in the rumen microflora, and animal physiological state (Johnson and Johnson, 1995). Therefore, given the complex biological interactions governing CH_4 production and the importance of representative datasets for achieving accurate and precise predictions, empirical models derived from narrowly defined experimental conditions may not adequately capture the heterogeneity inherent to modern beef production systems. Many published models have been developed using limited intake ranges, diet types, and/or specific breeds of cattle, which may limit the applicability of these models when applied to the global cattle population, modern production systems, and other independent databases.

Since beef cattle production presents large variability due to differences in production conditions such as management practices, resource availability, or geographical location, defining a single, universally applicable model to predict enteric CH_4 emissions is inherently challenging (Vargas et al., 2025). As demonstrated in the present study, no single prediction model minimized RMSPE while maximizing CCC across the stratified datasets, highlighting limitations inherent to single model approaches. Moreover, in the present study, regardless of the database utilized, when evaluating the predictive performance of 66 individual prediction models, enteric CH_4 was underpredicted by > 60% of prediction models. Similarly, Vargas et al. (2025) documented, in an evaluation of 72 prediction models, that 49 models underestimating enteric CH_4 emissions by 0.6 to 50.1% and 23 models overestimating emissions by 3.7 to 96.1%. However, when aggregating models estimated CH_4 production generated by all aggregations, except the NASEM model aggregation, were within ± 10% of observed CH_4 across all databases. Thus, aggregated models reduced RMSPE relative to most single prediction models; however, improvements in RMSPE exceeded those observed for CCC. Consequently, limitations in model agreement persist, with CCC values ranging from slight to adequate agreement depending on the database evaluated. Based on the classification suggested by Proctor et al. (2024), CCC values are interpreted as follows: < 0 indicates no agreement, 0 to 0.39 slight agreement, 0.40 to 0.59 moderate agreement, 0.60 to 0.80 adequate agreement, and > 0.80 excellent agreement.

Despite the ongoing challenge to develop a prediction model that can handle diversity in animals and diets, all the top-performing model aggregations incorporated models requiring the quantification of DMI. Dry matter intake is a primary factor influencing CH_4 production because it reflects the quantity of organic matter available for fermentation in the rumen of cattle (Johnson and Johnson, 1995; Beauchemin et al., 2022). Consequently, cattle with greater DMI are expected to produce greater total enteric CH_4 emissions (Vargas et al., 2025). Consistent with this biological basis, Vargas et al. (2025), in an evaluation of 72 prediction models using an independent database of 446 individual animal records, reported that DMI was positively and significantly associated with enteric CH_4 production in finishing steers. Moreover, although not evaluated in the present study, the positive association between DMI and CH_4 production may limit applicability in non-confinement systems and at commercial scales, where individual DMI measurements are not readily obtainable.

When considering the 66 prediction models evaluated in the present analysis, reported DMI during model development ranged from 1.62 to 20.1 kg/d (Ellis et al., 2007; Ellis et al., 2009; Yan et al., 2009; Ricci et al., 2013; Moraes et al., 2014; Escobar-Bahamondes et al., 2016; van Lingen et al., 2019; Hales et al., 2022; Galyean and Hales, 2022); when excluding the range reported by Ricci et al. (2013) DMI varied between 1.62 to 15.6 kg/d. In the present study, DMI ranged from 5.1 to 19.7 kg/d, 7.7 to 19.7 kg/d, and 5.1 to 11.0 kg/d for the entire database, the stratified *Bos taurus* database, and the stratified *Bos indicus* database, respectively. Differences in DMI distributions between datasets used for model development and the independent dataset evaluated in the present analysis may increase MB, particularly when predictions are applied outside the calibration range of the original model, potentially shifting predicted means relative to observed means (Tedeschi, 2006).

For the entire database (n = 888) and the stratified *Bos taurus* database (n = 755), the observed intake ranges were wider than those used to develop most of the evaluated prediction models, increasing the likelihood of extrapolation and potential underprediction of enteric CH_4 emissions when model calibration occurred at lesser intake ranges. Conversely, the stratified *Bos indicus* database (n = 133) exhibited a narrower intake range and a smaller mean than several datasets used for model development; therefore, when model development datasets were characterized by wider or higher intake distributions, overprediction of emissions may occur when applying those models to this stratified independent database.

Amongst the model aggregations generated for each database, four models were consistently ranked in the top 9 performing models across all strata of the database, those models being model 28 (Ellis et al., 2009; Equation A), model 59 (Ellis et al., 2007; Equation 7b), model 60 (Ellis et al., 2007; Equation 8b), and model 61 (Ellis et al., 2007; Equation 9b). A commonality across these four models is the requirement for DMI quantification.

Accurate estimation of enteric CH_4 emissions is essential for national GHG inventories, corporate sustainability reporting, and MRV programs (Vargas et al., 2025). Within global GHG accounting methodologies, the Tier 1 approach described by the Intergovernmental Panel on Climate Change (IPCC) applies standardized emission factors at the national scale but lacks resolution for animal-level or diet-specific prediction (IPCC, 2019: model 3). The Tier 2 methodology (model 2) incorporates feed intake; however, it remains dependent on generalized CH_4 conversion factors that may not reflect the finishing phase of modern beef production systems (IPCC, 2019; Schilling-Hazlett et al., 2025a; Schilling-Hazlett et al., 2025b). Consequently, there is a need for approaches that improve predictive accuracy and performance across diversity in cattle and diet types without sacrificing practical applicability.

Results of the present study indicate that model aggregation represents a pragmatic intermediate strategy between simplified emission factor approaches and reliance on a single empirical equation across heterogeneous production scenarios. By integrating multiple equations, that include animal-specific data, and weighting model performance based on independent evaluation metrics, aggregation reduced RMSPE and improved CCC when compared to observed CH_4 emissions at the mean level. Moreover, improved estimation of enteric CH_4 emissions has important implications for life cycle assessment modeling and carbon footprint calculations of beef production systems. Nonetheless, the persistence of slope bias, particularly within the stratified *Bos indicus* database, and only slight to adequate CCC values, according to criteria established by Proctor et al. (2024), suggest that further refinement is required before aggregated approaches can achieve high accuracy and precision at the individual-animal level across diverse production environments. Continued development of robust prediction models will depend on sustained direct measurement of enteric CH_4 emissions, necessitating increased investment in research and methodological development.

Ultimately, the objective of this analysis was not to develop a novel enteric CH_4 prediction model, given the similar experimental conditions and limited variability in dietary characteristics across the seven experiments represented in the present study. Rather, the aim of this study was to evaluate limitations and opportunities associated with utilizing existing prediction models to estimate enteric CH_4 from steers in the finishing phase of beef cattle production, which necessitated the development of models or model aggregation methodologies specifically developed for this phase where concentrate-based rations are standard. Moreover, while the present study provides valuable insights, limitations should be acknowledged. The stratified *Bos indicus* database (n = 133) was comparatively small, which may have affected the model evaluation metrics utilized. Additionally, although the prediction equations evaluated were reported for the general use in beef cattle, the independent databases in which the 66 evaluated prediction models were derived from exclusively included *Bos taurus* cattle, which may limit extrapolation across breeds and be a logical explanation for the greater SB observed. Furthermore, mitigation strategies (e.g., feed additives) were not represented in the dataset, restricting inference of the observations of the present study.

Despite these limitations, the present study possesses several notable strengths. The independent database included individual animal growth performance and enteric CH_4 emissions from 888 finishing steers, allowing model evaluation at the individual-animal level rather than relying solely on treatment means. This approach improves the robustness of precision and accuracy assessments by capturing biologically relevant variability that exists from animal to animal. Moreover, the focus on the finishing phase addresses a critical knowledge gap, as limited information exists regarding the sensitivity and performance of published models in feedlot conditions utilizing a concentrate-based diet (Vargas et al., 2025). Finally, comprehensive decomposition of RMSPE into MB, SB, and RB provided additional insight into prediction error structure beyond overall error magnitude, enabling a more nuanced evaluation of model performance (Tedeschi, 2006).

While single prediction models remain limited in their ability to accurately and precisely estimate enteric CH_4 emissions from finishing beef steers fed a concentrate-based diet, aggregation approaches offer improved predictive performance and practical applicability. Continued refinement of enteric CH_4 prediction models and aggregation methodologies, informed by direct measurement and individual-animal data, will be essential to further improve accuracy and support greenhouse gas measurement and mitigation efforts across beef production systems.

CONCLUSION

Aggregated enteric CH_4 prediction models consistently outperformed most single model approaches, reducing overall RMSPE and providing improved estimation of the observed enteric CH_4 emissions across the entire database (n = 888), stratified *Bos taurus* database (n = 755), and stratified *Bos indicus* database (n = 133). Despite notable improvements in RMSPE, residual slope bias and variability in CCC indicate that further refinement is needed to achieve high accuracy and precision at the individual-animal level. Dry matter intake quantification was required in the top performing models across all databases, highlighting the importance of incorporating animal-specific feed intake data when estimating CH_4 production in finishing steers while also highlighting the practical challenge of obtaining this input at a commercial scale and in non-confinement beef production systems. Overall, these observations demonstrate that model aggregation represents a pragmatic strategy to enhance predictive performance, while continued measurement and model development remain critical for robust greenhouse gas quantification and mitigation in beef production systems.

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Table 4.1. Diet composition of the finishing rations utilized across seven experiments with beef steers

	Experimental Finishing Rations[1]																
	E1		E2				E3	E4	E5				E6	E7			
Item	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R7**	**R8**	**R9**	**R10**	**R11**	**R12**	**R13**	**R14**	**R15**	**R16**
Ingredient (% of DM)																	
Steam-flaked corn	60.0	60.0	65.0	65.0	65.0	65.0	65.0	65.0	51.0	51.0	51.0	51.0	51.0	61.0	65.0	61.0	61.0
Corn silage	27.0	27.0	20.0	20.0	20.0	20.0	20.0	20.0	19.1	19.1	19.1	19.1	19.1	20.0	20.0	20.0	20.0
Dried distiller's grains with solubles	4.0	4.0	7.0	7.0	7.0	7.0	7.0	7.0	26.3	26.3	26.3	26.3	26.3	7.0	7.0	7.0	7.0
Mineral supplement[2]	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0	-	-	-	-	-	4.0	4.0	4.0	4.0
Pellet supplement[3]	-	-	4.0	-	4.0	-	-	-	-	-	-	-	-	-	-	-	-
Pellet supplement[4]	4.0	4.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pellet supplement[5]	-	-	-	4.0	-	4.0	4.0	4.0	-	-	-	-	-	4.0	4.0	4.0	4.0
Supplement[6]	2.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Supplement[7]	-	2.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Supplement[8]	-	-	-	-	-	-	-	-	3.6	3.6	3.6	3.6	-	-	-	-	-
Supplement[9]	-	-	-	-	-	-	-	-	-	-	-	-	3.6	-	-	-	-
Fat[10]	-	-	-	-	-	-	-	-	-	-	-	-	-	4.0	-	4.0	4.0

[1]E = experiment; R = finishing ration
[2]Molasses-based mineral supplement. MidWest PMS, Englewood, CO
[3]Without ionophore and tylosin phosphate. Ralco, Marshall, MN
[4]With tylosin phosphate. Ralco, Marshall, MN
[5]With ionophore and tylosin phosphate. Ralco, Marshall, MN
[6]With ionophore.
[7]Without ionophore.
[8]With non-protein nitrogen (NPN). Cargill, Minnetonka, MN
[9]Without non-protein nitrogen (NPN). Cargill, Minnetonka, MN
[10]Fat utilized was soybean oil, beef tallow, or palm oil

Table 4.2. Dietary nutrient composition of the finishing rations utilized across seven experiments with beef steers

	Experimental Finishing Rations[1]																
	E1		E2				E3	E4	E5				E6	E7			
Item	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R7**	**R8**	**R9**	**R10**	**R11**	**R12**	**R13**	**R14**	**R15**	**R16**
Composition[2] (% of DM)																	
Dry matter, %	65.2	65.2	65.7	65.7	64.3	64.3	66.5	62.9	71.6	71.0	71.8	72.4	65.2	68.1	67.8	68.3	68.6
Crude protein	12.8	12.8	14.4	13.9	14.2	14.5	13.7	13.7	13.3	13.9	14.9	13.2	13.9	13.7	13.4	13.9	13.6
Neutral detergent fiber	15.9	17.7	14.2	14.4	15.9	18.5	17.5	17.5	17.1	17.2	16.2	17.2	14.4	15.2	14.8	15.8	16.8
Acid detergent fiber	9.4	10.4	8.9	8.8	7.8	7.9	8.8	8.8	8.1	7.8	7.9	7.8	8.8	8.4	7.7	9.8	7.9
Lignin	1.5	1.7	2.1	2.5	1.3	1.4	1.4	1.4	2.6	2.6	2.6	2.6	2.5	1.9	1.8	2.1	2.0
Non-fiber carbohydrates	63.3	61.1	62.3	62.9	60.9	58.1	61.3	61.3	56.4	56.3	56.2	56.5	62.9	59.2	63.4	56.5	57.7
Starch	55.9	54.7	56.1	59.1	51.8	54.6	53.8	53.8	46.0	45.9	45.8	47.5	59.1	50.1	54.3	46.7	48.2
Sugar	1.2	1.2	0.9	0.9	0.9	0.9	0.9	0.9	1.1	1.1	1.1	1.1	0.9	0.9	0.9	0.9	0.9
Ether extract	4.2	4.3	4.6	4.2	4.5	4.5	3.1	3.1	5.1	5.1	5.1	5.1	4.2	7.2	4.3	9.1	7.3
Ash	3.8	4.1	4.6	4.7	4.5	4.5	4.5	4.5	2.9	2.9	2.9	2.9	4.7	4.7	4.1	4.8	4.6
Total digestible nutrients	82.4	81.7	83.0	81.0	83.0	82.0	81.0	81.0	76.5	76.5	77.2	76.8	81.0	86.0	83.0	87.5	85.5
Gross energy, Mcal/kg	4.6	4.6	4.4	4.5	4.4	4.4	4.4	4.4	4.6	4.6	4.6	4.6	4.5	4.8	4.5	4.8	4.8
Net energy of maintenance, Mcal/kg	2.0	2.0	2.1	2.0	2.1	2.1	2.0	2.0	1.9	1.9	1.9	1.9	2.0	2.2	2.1	2.3	2.2
Net energy of gain, Mcal/kg	1.4	1.4	1.4	1.4	1.4	1.4	1.3	1.3	1.2	1.2	1.3	1.2	1.4	1.5	1.4	1.6	1.5

[1]E = experiment; R = finishing ration

[2]Ration composition determined via wet chemistry. For E5; lignin, non-fiber carbohydrates, ether extract, and ash were simulated using the National Academies of Science, Engineering, and Medicine Beef Cattle Nutrient Requirements Model 2016 v.1.0.37.21. For all experiments sugar was simulated using the National Academies of Science, Engineering, and Medicine Beef Cattle Nutrient Requirements Model 2016 v.1.0.37.21.

Table 4.3. Methane prediction models for beef cattle

Model	Source	Equation[1]
1	EPA, 2024	[DMI (kg/d) × GE (MJ/kg of DM) × (0.039)]
2	IPCC, 2019	[DMI (kd/d) × GE (MJ/kg of DM) × (0.03)]
3	IPCC, 2019	[64 (kg/year) / 365] × 55.65
4	Hales et al, 2022	[0.2433 × DMI (kg/d)] × 4.184
5	Hales et al, 2022	[(0.3344 − 0.05639 × L) × DMI (kg/d)] × 4.184
6	Galyean Hales, 2022	[(0.2883 − 0.03474 × St:NDF) × DMI (kg/d)] × 4.184
7	Galyean Hales, 2022	[0.3227 − 0.0334 × St:NDF − 0.00868 × EE (%)] × 4.184
8	Galyean Hales, 2022	[32.2935 + 15.7637 × DMI (kg/d) − 15.7420 × St:NDF] × 0.05565
9	Galyean Hales, 2022	[48.3465 + 15.3643 × DMI (kg/d) − 15.1229 × St:NDF − 3.4998 × EE (%)] × 0.05565
10	van Lingen 2019	[46.6 + 9.54 × DMI (kg/d)] × 0.05565
11	van Lingen 2019	[112 + 9.46 × DMI (kg/d) − 2.58 × NDF (%)] × 0.05565
12	van Lingen 2019	[42 + 9.85 × DMI (kg/d) + 0.0331 × St (%)] × 0.05565
13	van Lingen 2019	[57 + 8.84 × DMI (kg/d) − 1.17 × EE (%)] × 0.05565
14	van Lingen 2019	[0.045 × GEI (MJ/d)]
15	Escobar-Bahamondes, 2016	[(−26.4 + 0.21 × BW (kg) + 30.1 × CPI (kg/d) − 70.5 × EEI^2 (kg/d) + 10.1 × (NDFI (kg/d) − $ADFI^3$ (kg/d))] × 0.05565
16	Escobar-Bahamondes, 2016	[(−10.1 + 0.21 × BW (kg) +0.36 × DMI^2 (kg/d) − 69.2 × EEI^3 (kg/d)+ 13 × (CP:NDF) − 4.9 × (St:NDF))] × 0.05565
17	Moraes, 2014	[0.743 + 0.054 × GEI (MJ/d)]
18	Moraes, 2014	[−0.221 + 0.048 × GEI (MJ/d) + 0.005 × BW (kg)]
19	Ricci 2013	[74.34 + 0.57 × GEI (MJ/d) + 10.61 × Feed − 69.67 × Stage − 0.22 × GEI (MJ/d) × Feed + 0.57 × GEI (MJ/d) × Stage] × 0.05565
20	Ricci 2013	[79.87 + 9.95 × DMI (kg/d) − 15.15 × Feed − 74.48 × Stage − 3.67 × DMI (kg/d) × feed + 10.90 × DMI (kg/d) × Stage] × 0.05565
21	Ricci 2013	[88.41 + 0.75 × DEI (MJ/d) − 19.28 × Feed − 39.19 × Stage − 0.29 × DEI (MJ/d) × Feed + 0.69 × DEI (MJ/d) × Stage] × 0.05565
22	Yan 2009	[0.378 × BW (kg) + 64.8] × 0.03960
23	Yan 2009	[35.1 × DMI (kg/d) + 14.7] × 0.0396
24	Yan 2009	{[31 − 311.5 × ME:GE + 206.8 × DE:GE + 4.3 × ME (MJ/kg of DM)] × DMI (kg/d) −13.7} × 0.0396
25	Yan 2009	[1.959 × GEI (MJ/d) + 8.8] × 0.0396
26	Yan 2009	{[1.635 − 12.62 × ME:GE + 11.26 × DE:GE] × GEI (MJ/d) − 13.8} × 0.0396
27	Yan 2009	{[0.877 − 14.66 × ME:GE + 13.55 × DE:GE + 0.457 × FP (kg/kg of DM) + 4.153 × NDF (kg/kg of DM) − 7.47 × ADF (kg/kg of DM)] × GEI (MJ/d) + 0.8} × 0.0396
28	Ellis 2009	[2.29 + 0.670 × DMI (kg/d)]
29	Ellis 2009	[3.05 + 3.71 × CI (kg/d)]
30	Ellis 2009	[4.72 + 1.13 × StI (kg/d)]
31	Ellis 2009	[6.01 + 0.345 × NFCI (kg/d)]
32	Ellis 2009	[3.46 + 5.06 × SugI]

Model	Source	Equation[1]
33	Ellis 2009	[−1.01 + 2.76 × NDFI (kg/d) + 0.722 × StI (kg/d)]
34	Ellis 2009	[2.26 + 5.02 × SugI + 0.0236 × FP]
35	Ellis 2009	[2.72 + 0.0937 × MEI (MJ/d) + 4.31 × CI (kg/d) − 6.49 × HI (kg/d) − 7.44 × EEI (kg/d)]
36	Ellis 2009	[0.310 + 2.88 × CI (kg/d) + 4.15 × CPI (kg/d) − 3.97 × EEI (kg/d)]
37	Ellis 2009	[0.561 + 5.86 × CI (kg/d) + 0.526 × NFCI (kg/d)]
38	Ellis 2009	[2.79 − 1.04 × (NFC:NDF) + 0.798 × DMI (kg/d)]
39	Ellis 2009	[2.68 − 1.14 × (St:NDF) + 0.786 × DMI (kg/d)]
40	Ellis 2009	[2.58 − 0.339 × (NFC:ADF) + 0.774 × DMI (kg/d)]
41	Ellis 2009	[2.50 − 0.367 × (St:ADF) + 0.766 × DMI (kg/d)]
42	Ellis 2009	$[7.09 \times \{1 - \exp^{[-18.9 \times \text{EEI (kg/d)}]}\}]$
43	Ellis 2009	$[8.53 \times \{1 - \exp^{[-0.637 \times \text{NDFI (kg/d)}]}\}]$
44	Ellis 2009	$[8.76 \times \{1 - \exp^{[-1.86 \times \text{HI (kg/d)}]})]$
45	Ellis 2009	$[8.51 \times \{1 - \exp^{[-5.50 \times \text{LgI (kg/d)}]}\}]$
46	Ellis 2009	$[8.23 \times \{1 - \exp^{[-1.68 \times \text{ADFI (kg/d)}]}\}]$
47	Ellis 2009	$[8.48 \times \{1 - \exp^{[-0.0230 \times \text{MEI (MJ/d)}]}\}]$
48	Ellis 2009	$[10.8 \times \{1 - \exp^{[-0.141 \times \text{DMI (kg/d)}]}\}]$
49	Ellis 2009	$[9.44 \times \exp^{(-0.5 \times [(\text{FP (\%)} - 48.7]/33.3\text{\^{}}2)}]$
50	Ellis 2009	$[10.8 \times (1 - \exp^{\{-[-0.0127 \times (\text{NFC:ADF}) + 0.220] \times \text{DMI (kg/d)}\}})]$
51	Ellis 2009	$[10.8 \times (1 - \exp^{\{-[-0.0138 \times (\text{St:ADF}) + 0.211] \times \text{DMI (kg/d)}\}})]$
52	Ellis 2009	$[10.8 \times (1 - \exp^{\{-[-0.034 \times (\text{NFC:NDF}) + 0.228] \times \text{DMI (kg/d)}\}})]$
53	Ellis 2007	[4.38 + 0.0586 × ME intake (MJ/d)]
54	Ellis 2007	[3.96 + 0.561 × DMI (kg/d)]
55	Ellis 2007	[4.79 + 0.0492 × FP (%)]
56	Ellis 2007	[5.263 + 6.93 × LgI (kg/d)]
57	Ellis 2007	[5.58 + 0.848 × NDFI (kg/d)]
58	Ellis 2007	[5.70 + 1.41 × ADFI (kg/d)]
59	Ellis 2007	[3.05 + 0.0371 × MEI (MJ/d) + 0.801 × NDFI (kg/d)]
60	Ellis 2007	[3.31 + 0.0382 × MEI (MJ/d) + 1.05 × ADFI (kg/d)]
61	Ellis 2007	[0.357 + 0.0591 × MEI (MJ/d) + 0.0500 × FP (%)]
62	Ellis 2007	[−1.02 + 0.681 × DMI (kg/d) + 0.0481 × FP (%)]
63	Ellis 2007	[2.30 + 1.12 × DMI (kg/d) − 6.26 × LgI (kg/d)]
64	Ellis 2007	[2.70 + 1.16 × DMI (kg/d) − 15.8 × EEI (kg/d)]
65	Ellis 2007	[0.183 + 0.0433 × MEI (MJ/d) + 0.647 × NDFI (kg/d) + 0.0372 × FP (%)]
66	Ellis 2007	[2.94 + 0.0585 × MEI (MJ/d) + 1.44 × ADFI (kg/d) − 4.16 × LgI (kg/d)]

[1]ADFI: acid detergent fiber intake; BW: Body weight; CI: Cellulose intake; CP: crude protein concentration; CPI: crude protein intake; DEI: digestible energy intake; DMD: digestibility of dry matter; DM: Dry matter; DMI: Dry matter intake; ED: Energy digestibility; EE: ether extract concentration; EEI: ether extract intake; Feed: correction factor by feed type (1 in high concentrate diets); FP: forage proportion; GE: Gross energy concentration; GEI: gross energy intake; HI: Hemicellulose intake; L: intake level; LgI: lignin intake; ME: metabolizable energy concentration; MEI: metabolizable energy intake; NDF: neutral detergent fiber concentration; NDFI: neutral detergent fiber intake; NFCI: non-fiber carbohydrate intake; Stage: correction factor for stage (0 for non-lactating animal); St: starch concentration; StI: starch intake.

Table 4.4. Methane production and growth performance descriptive statistics of 888 finishing steers in an independent database

Variable[1]	Mean	Min	Max	SD
CH_4 production, g/d	177	53	307	37.5
CH_4 production, MJ/d	10	3	17	2.1
IBW, kg	492	312	721	55.9
FBW, kg	658	368	882	78.1
ADG, kg/d	1.9	0.1	3.6	0.56
DMI, kg/d	12.0	5.1	19.7	2.63
G:F, kg/kg	0.178	0.019	0.316	0.0458

[1]CH_4= enteric methane, IBW= initial body weight, FBW= final body weight, ADG= average daily gain, DMI= dry matter intake, G:F= gain to feed ratio (feed efficiency).

Table 4.5. Methane production and growth performance descriptive statistics of 755 *Bos taurus* finishing steers in an independent database

Variable[1]	Mean	Min	Max	SD
CH_4 production, g/d	185	115	307	32.6
CH_4 production, MJ/d	10	6	17	1.8
IBW, kg	502	322	721	52.2
FBW, kg	678	505	882	61.5
ADG, kg/d	2.1	0.5	3.6	0.45
DMI, kg/d	12.8	7.7	19.7	1.97
G:F, kg/kg	0.183	0.061	0.316	0.0449

[1]CH_4= enteric methane, IBW= initial body weight, FBW= final body weight, ADG= average daily gain, DMI= dry matter intake, G:F= gain to feed ratio (feed efficiency).

Table 4.6. Methane production and growth performance descriptive statistics of 133 *Bos indicus* finishing steers in an independent database

Variable[1]	Mean	Min	Max	SD
CH_4 production, g/d	131	53	213	28.6
CH_4 production, MJ/d	7	3	12	1.6
IBW, kg	435	312	525	40.6
FBW, kg	541	368	671	56.3
ADG, kg/d	1.1	0.1	1.8	0.32
DMI, kg/d	7.6	5.1	11.0	1.13
G:F, kg/kg	0.144	0.020	0.220	0.0350

[1]CH_4= enteric methane, IBW= initial body weight, FBW= final body weight, ADG= average daily gain, DMI= dry matter intake, G:F= gain to feed ratio (feed efficiency

Table 4.7. Pearson correlation coefficients between growth performance, dietary nutrient composition, and enteric methane production for 888 finishing steers in an independent database.

Variable[1]	Mean	Median	SD	Min	Max	r^2
CH_4, MJ/d	9.8	9.7	2.09	3.0	17.1	---
BW, kg	575	580	60.3	340	782	0.59*
ADG, kg/d	1.9	2.0	0.56	0.1	3.6	0.50*
DMI, kg/d	12.0	12.1	2.63	5.1	19.7	0.54*
G:F	0.2	0.2	0.03	0.0	0.3	0.20*
CP, % DM	13.7	13.7	0.59	12.8	14.9	-0.12*
EE, % DM	4.9	4.5	1.38	3.1	9.1	0.24*
Ash, % DM	4.2	4.5	0.63	2.9	4.8	-0.14*
NFC, % DM	60.3	61.1	2.57	56.2	63.4	-0.14*
SUG, % DM	1.0	0.9	0.11	0.9	1.2	0.01 ns
ST, % DM	53.0	54.3	4.18	45.8	59.1	-0.32*
FOR, % DM	10.6	10.0	1.41	9.6	13.5	-0.14*
NDF, % DM	16.3	15.9	1.38	14.2	18.5	0.06 ns
ADF, % DM	8.7	8.8	0.83	7.7	10.4	-0.14*
LIG, % DM	1.9	1.9	0.46	1.3	2.6	0.13
CELL, % DM	6.8	6.5	1.00	5.2	8.7	-0.18*
HEMI, % DM	7.6	7.4	1.62	5.3	10.6	0.13*
TDN, % DM	81.8	82.0	2.74	76.5	87.5	0.01 ns
GE, MJ/kg	19.0	19.0	0.48	18.5	20.1	0.33*
DE, MJ/kg	15.1	15.1	0.50	14.1	16.1	0.01 ns
ME, MJ/kg	12.4	12.4	0.41	11.5	13.2	0.01 ns

[1]CH_4 = enteric methane production, BW = body weight, ADG = average daily gain, DMI = dry matter intake, G:F = gain to feed ratio; feed efficiency, CP = crude protein, EE = ether extract, NFC = non-fiber carbohydrates, SUG = sugar, ST = starch, FOR = forage, NDF = neutral detergent fiber, ADF = acid detergent fiber, LIG = lignin, CELL = cellulose, HEMI = hemicellulose, TDN = total digestible nutrients, GE = gross energy, DE = digestible energy, ME = metabolizable energy.

[2]Pearson correlation between variables and CH_4 production, where ns = non-significant; $P > 0.05$, and * = $P \leq 0.05$.

Table 4.8. Pearson correlation coefficients between growth performance, dietary nutrient composition, and enteric methane production for 755 *Bos taurus* finishing steers in an independent database.

Variable[1]	Mean	Median	SD	Min	Max	r^2
CH_4, MJ/d	10.3	10.1	1.82	6.4	17.1	---
BW, kg	590	587	48.2	442	782	0.41*
ADG, kg/d	2.1	2.1	0.45	0.5	3.6	0.27*
DMI, kg/d	12.8	12.6	1.97	7.7	19.7	0.28*
G:F	0.2	0.2	0.03	0.1	0.3	0.11*
CP, % DM	13.6	13.7	0.58	12.8	14.9	0.09*
EE, % DM	4.9	4.5	1.48	3.1	9.1	0.22*
Ash, % DM	4.1	4.5	0.66	2.9	4.8	0 ns
NFC, % DM	60.1	61.1	2.63	56.2	63.4	-0.15*
SUG, % DM	1.0	0.9	0.12	0.9	1.2	-0.22*
ST, % DM	52.4	53.8	4.19	45.8	59.1	-0.20*
FOR, % DM	10.7	10.0	1.50	9.6	13.5	-0.29*
NDF, % DM	16.4	16.2	1.26	14.2	18.5	-0.13*
ADF, % DM	8.7	8.8	0.87	7.7	10.4	-0.23*
LIG, % DM	1.9	1.8	0.45	1.3	2.6	0.23*
CELL, % DM	6.8	6.5	1.08	5.2	8.7	-0.28*
HEMI, % DM	7.7	7.4	1.48	5.3	10.6	0.02 ns
TDN, % DM	81.7	81.7	2.95	76.5	87.5	0.05 ns
GE, MJ/kg	19.1	19.0	0.49	18.5	20.1	0.19*
DE, MJ/kg	15.0	15.0	0.54	14.1	16.1	0.05 ns
ME, MJ/kg	12.3	12.3	0.45	11.5	13.2	0.05 ns

[1]CH_4 = enteric methane production, BW = body weight, ADG = average daily gain, DMI = dry matter intake, G:F = gain to feed ratio; feed efficiency, CP = crude protein, EE = ether extract, NFC = non-fiber carbohydrates, SUG = sugar, ST = starch, FOR = forage, NDF = neutral detergent fiber, ADF = acid detergent fiber, LIG = lignin, CELL = cellulose, HEMI = hemicellulose, TDN = total digestible nutrients, GE = gross energy, DE = digestible energy, ME = metabolizable energy.

[2]Pearson correlation between variables and CH_4 production, where ns = non-significant; $P > 0.05$, and * = $P \leq 0.05$.

Table 4.9. Pearson correlation coefficients between growth performance, dietary nutrient composition, and enteric methane production for 133 *Bos indicus* finishing steers in an independent database.

Variable[1]	Mean	Median	SD	Min	Max	r^2
CH_4, MJ/d	7.3	7.2	1.59	3.0	11.9	---
BW, kg	488	490	46.7	340	598	0.39*
ADG, kg/d	1.1	1.1	0.32	0.1	1.8	0.20*
DMI, kg/d	7.6	7.5	1.13	5.1	11.0	0.43*
G:F	0.1	0.1	0.03	0.0	0.2	0.03 ns
CP, % DM	14.3	14.4	0.25	13.9	14.5	0.11 ns
EE, % DM	4.4	4.5	0.17	4.2	4.6	0 ns
Ash, % DM	4.6	4.6	0.05	4.5	4.7	-0.27*
NFC, % DM	61.1	62.3	2.00	58.1	62.9	-0.39*
SUG, % DM	0.9	0.9	0.00	0.9	0.9	---
ST, % DM	56.0	56.1	2.48	51.8	59.1	-0.19*
FOR, % DM	10.0	10.0	0.00	10.0	10.0	---
NDF, % DM	15.7	14.4	1.81	14.2	18.5	0.42*
ADF, % DM	8.4	8.8	0.50	7.8	8.9	-0.40*
LIG, % DM	1.9	2.1	0.50	1.3	2.5	-0.30*
CELL, % DM	6.5	6.5	0.19	6.3	6.8	-0.26*
HEMI, % DM	7.3	5.6	2.26	5.3	10.6	0.42*
TDN, % DM	82.1	82.0	0.85	81.0	83.0	0.12 ns
GE, MJ/kg	18.6	18.6	0.08	18.5	18.7	0.11 ns
DE, MJ/kg	15.1	15.1	0.16	14.9	15.3	0.12 ns
ME, MJ/kg	12.4	12.4	0.13	12.2	12.5	0.12 ns

[1]CH_4 = enteric methane production, BW = body weight, ADG = average daily gain, DMI = dry matter intake, G:F = gain to feed ratio; feed efficiency, CP = crude protein, EE = ether extract, NFC = non-fiber carbohydrates, SUG = sugar, ST = starch, FOR = forage, NDF = neutral detergent fiber, ADF = acid detergent fiber, LIG = lignin, CELL = cellulose, HEMI = hemicellulose, TDN = total digestible nutrients, GE = gross energy, DE = digestible energy, ME = metabolizable energy.

[2]Pearson correlation between variables and CH_4 production, where ns = non-significant; $P > 0.05$, and * = $P \leq 0.05$.

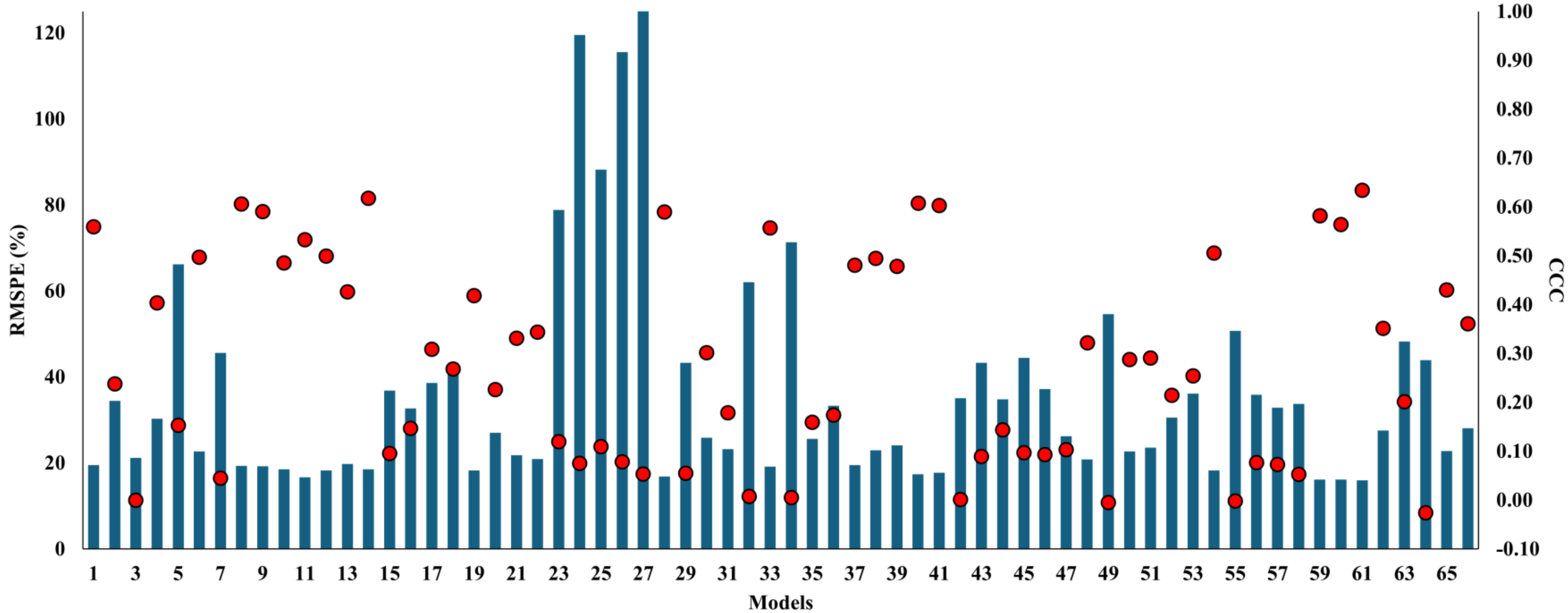

Figure 4.1. Root mean square prediction error as a percentage of the observed mean (RMSPE [%]; bars) and concordance correlation coefficient (CCC; dots) for 66 models predicting enteric methane emissions. Models were evaluated using an independent database containing 888 individual records from finishing beef steers fed a concentrate-based diet.

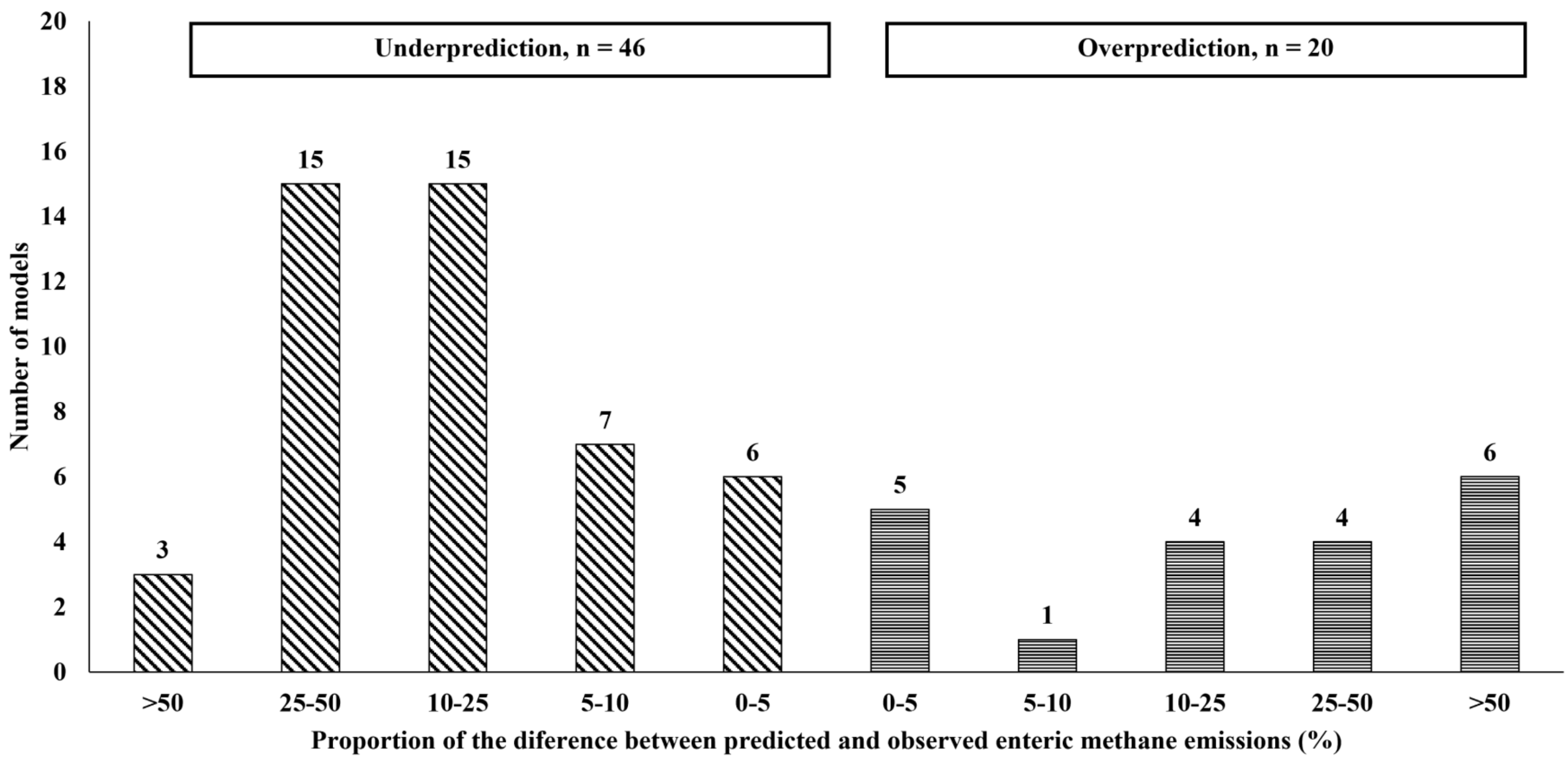

Figure 4.2. Number of models that underpredicted or overpredicted enteric CH_4 emissions, classified by the proportional difference between predicted and observed values. A total of 66 models were evaluated using an independent database containing 888 individual records from finishing beef steers fed a concentrate-based diet.

Table 4.10. Weighted ranking of methane prediction models based on concordance correlation coefficient, root mean square prediction error, mean bias, slope bias, and residual bias, using an independent database containing 888 individual animal records.

Model	Observed[1]	Predicted[1]	RMSPE[1], %	RMSPE, MJ/d	MB[1], % MSE	SB[1], % MSE	RB[1], % MSE	CCC[1]	Overall Rank
61	9.84	9.63	15.99	1.57	1.91	0.94	97.15	0.63	1
40	9.84	9.49	17.35	1.71	4.39	5.78	89.83	0.61	2
59	9.84	10.10	16.11	1.59	2.67	0.53	96.80	0.58	3
60	9.84	10.05	16.12	1.59	1.63	1.57	96.80	0.56	4
28	9.84	10.33	16.87	1.66	8.44	0.45	91.12	0.59	5
41	9.84	9.43	17.74	1.75	5.67	7.50	86.84	0.60	6
14	9.84	10.29	18.55	1.83	5.99	15.81	78.21	0.62	7
11	9.84	10.21	16.64	1.64	5.09	2.05	92.85	0.53	8
8	9.84	9.44	19.32	1.90	4.58	21.21	74.21	0.61	9
9	9.84	9.23	19.21	1.89	10.46	14.36	75.18	0.59	10
12	9.84	9.01	18.26	1.80	21.55	0.82	77.63	0.50	11
54	9.84	10.69	18.29	1.80	22.01	0.50	77.49	0.51	12
33	9.84	8.93	19.13	1.88	23.70	3.53	72.77	0.56	13
1	9.84	8.92	19.46	1.92	23.34	5.61	71.05	0.56	14
10	9.84	8.96	18.53	1.82	23.41	1.12	75.47	0.49	15
19	9.84	9.18	18.27	1.80	13.57	5.79	80.63	0.42	16
37	9.84	9.06	19.45	1.91	16.93	2.10	80.97	0.48	17
13	9.84	8.76	19.77	1.95	31.19	2.62	66.19	0.43	18
6	9.84	8.81	22.69	2.23	21.35	18.66	59.99	0.50	19
38	9.84	8.47	22.92	2.26	37.05	9.36	53.59	0.49	20
65	9.84	8.25	22.73	2.24	51.05	0.00	48.95	0.43	21
22	9.84	11.17	20.93	2.06	41.33	34.19	24.49	0.34	22
48	9.84	8.66	20.83	2.05	33.14	14.37	52.49	0.32	23
39	9.84	8.36	24.07	2.37	39.39	11.33	49.29	0.48	24
21	9.84	8.46	21.83	2.15	41.26	7.68	51.06	0.33	25
50	9.84	8.40	22.68	2.23	41.63	6.22	52.15	0.29	26
51	9.84	8.26	23.53	2.32	46.65	3.77	49.58	0.29	27
62	9.84	7.66	27.55	2.71	64.99	0.31	34.70	0.35	28
66	9.84	12.12	28.03	2.76	67.91	0.34	31.75	0.36	29
4	9.84	12.21	30.25	2.98	63.12	8.55	28.33	0.40	30
30	9.84	11.82	25.86	2.55	60.54	2.25	37.21	0.30	31
31	9.84	8.49	23.17	2.28	35.10	18.80	46.10	0.18	32
20	9.84	7.79	27.00	2.66	59.52	4.91	35.57	0.23	33
35	9.84	9.65	25.60	2.52	0.61	32.84	66.54	0.16	34
52	9.84	7.41	30.53	3.01	65.74	0.00	34.26	0.21	35
2	9.84	6.86	34.46	3.39	77.33	0.02	22.65	0.24	36
17	9.84	13.09	38.61	3.80	73.04	8.91	18.05	0.31	37
47	9.84	8.10	26.22	2.58	45.42	26.43	28.15	0.10	38
36	9.84	7.07	33.29	3.28	71.89	0.35	27.75	0.17	39

[1]Observed= observed enteric CH_4 emissions, Predicted= predicted enteric CH_4 emissions utilizing the corresponding enteric CH_4 prediction model, RMSPE= root mean square prediction error, MB= mean bias, SB= slope bias, RB= residual bias, CCC= concordance correlation coefficient.

Model	Observed[1]	Predicted[1]	RMSPE[1], %	RMSPE, MJ/d	MB[1], % MSE	SB[1], % MSE	RB[1], % MSE	CCC[1]	Overall Rank
53	9.84	13.05	36.09	3.55	81.22	0.11	18.67	0.25	40
16	9.84	7.57	32.67	3.22	49.99	10.98	39.03	0.15	41
18	9.84	13.63	42.72	4.21	81.02	5.24	13.74	0.27	42
3	9.84	9.76	21.18	2.09	0.17	--	--	0.00	43
44	9.84	6.92	34.81	3.43	72.60	0.18	27.21	0.14	44
57	9.84	7.24	32.81	3.23	65.09	6.66	28.25	0.07	45
63	9.84	14.28	48.26	4.75	87.29	1.96	10.74	0.20	46
15	9.84	6.93	36.80	3.62	64.52	4.56	30.93	0.10	47
56	9.84	6.87	35.90	3.53	70.86	0.80	28.35	0.08	48
46	9.84	6.66	37.16	3.66	75.58	3.62	20.80	0.09	49
58	9.84	7.16	33.71	3.32	65.43	6.01	28.56	0.05	50
43	9.84	5.96	43.30	4.26	83.14	1.70	15.16	0.09	51
45	9.84	5.87	44.45	4.38	82.51	0.01	17.49	0.10	52
5	9.84	16.00	66.21	6.52	89.09	5.05	5.87	0.15	53
42	9.84	7.09	35.09	3.45	63.77	19.27	16.97	0.00	54
23	9.84	17.25	78.85	7.76	91.13	4.70	4.17	0.12	55
29	9.84	6.03	43.31	4.26	79.96	0.43	19.61	0.06	56
25	9.84	18.09	88.24	8.69	90.10	6.44	3.46	0.11	57
7	9.84	6.47	45.58	4.49	56.39	22.26	21.35	0.05	58
26	9.84	20.77	115.54	11.37	92.28	5.76	1.96	0.08	59
64	9.84	7.22	43.88	4.32	36.85	39.93	23.22	-0.03	60
32	9.84	4.08	62.06	6.11	89.06	1.55	9.38	0.01	61
24	9.84	21.14	119.52	11.77	92.22	5.94	1.84	0.08	62
55	9.84	5.31	50.73	4.99	82.41	0.53	17.06	0.00	63
34	9.84	3.12	71.31	7.02	91.66	0.77	7.57	0.01	64
49	9.84	4.90	54.65	5.38	84.32	0.98	14.70	0.00	65
27	9.84	22.83	135.30	13.32	94.98	3.54	1.48	0.05	66

[1]Observed= observed enteric CH_4 emissions, Predicted= predicted enteric CH_4 emissions utilizing the corresponding enteric CH_4 prediction model, RMSPE= root mean square prediction error, MB= mean bias, SB= slope bias, RB= residual bias, CCC= concordance correlation coefficient.

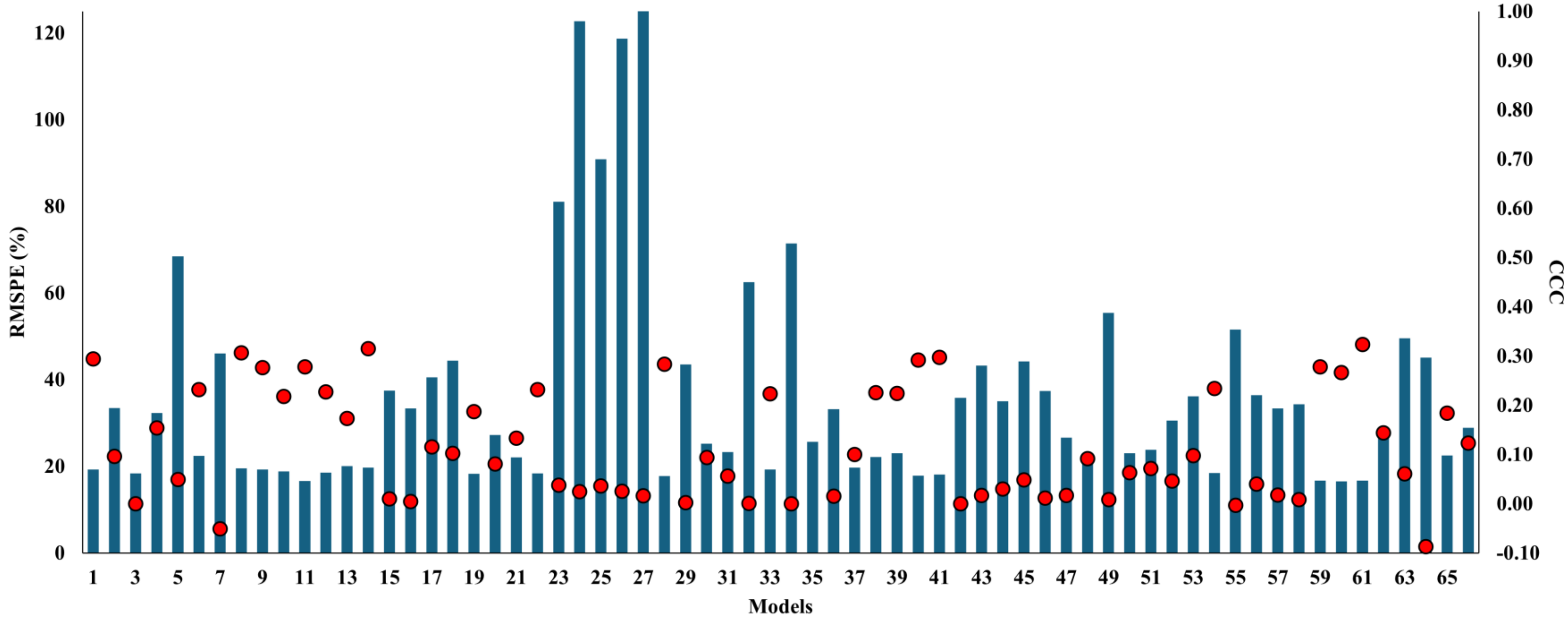

Figure 4.3. Root mean square prediction error as a percentage of the observed mean (RMSPE [%]; bars) and concordance correlation coefficient (CCC; dots) for 66 models predicting enteric methane emissions. Models were evaluated using an independent database containing 755 individual animal records from *Bos taurus* finishing beef steers fed a concentrate-based diet.

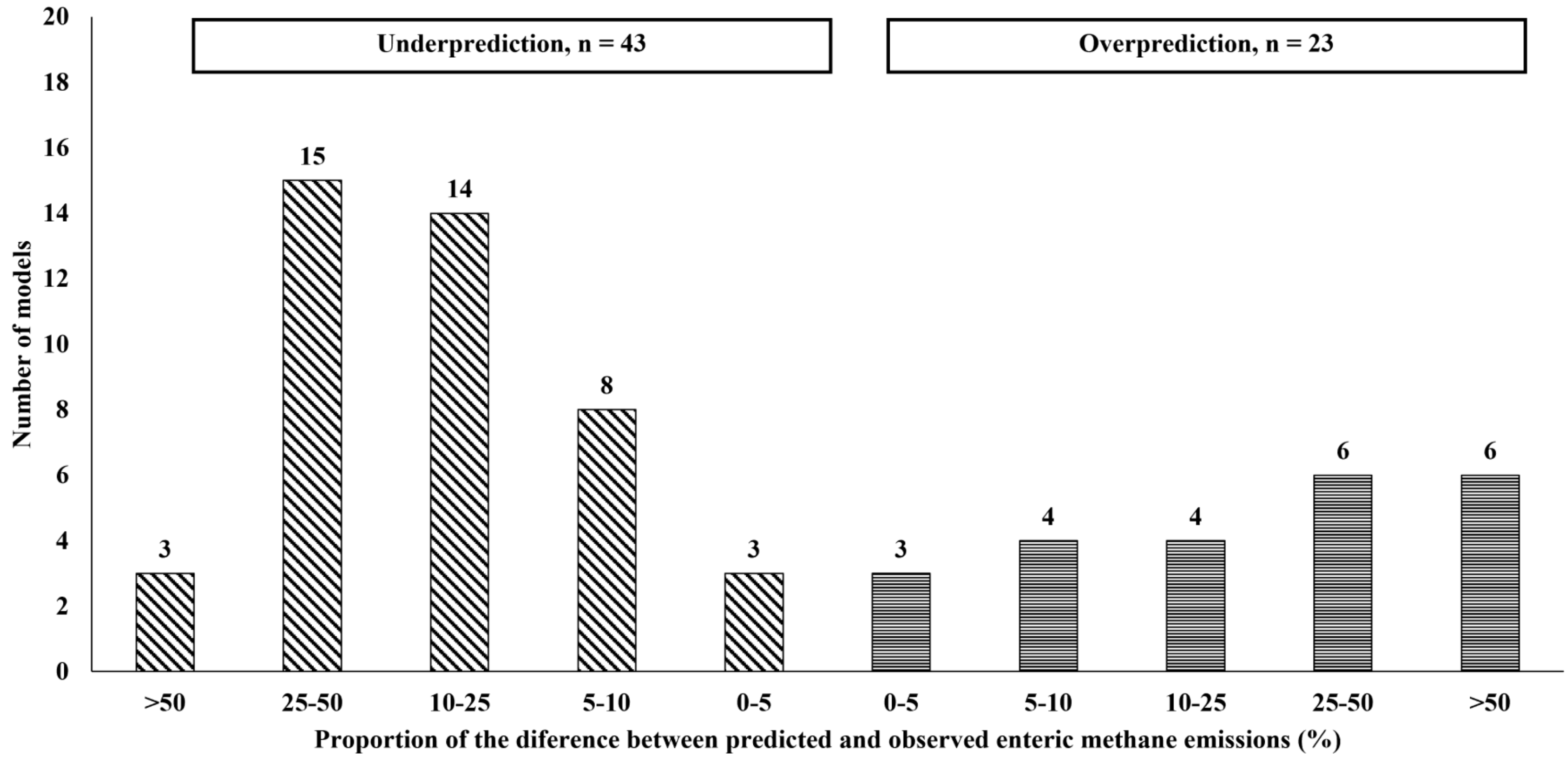

Figure 4.4. Number of models that underpredicted or overpredicted enteric CH_4 emissions, classified by the proportional difference between predicted and observed values. A total of 66 models were evaluated using an independent database containing 755 individual animal records from *Bos taurus* finishing beef steers fed a concentrate-based diet

Table 4.11. Weighted ranking of methane prediction models based on concordance correlation coefficient, root mean square prediction error, mean bias, slope bias, and residual bias, using an independent database containing 755 individual *Bos taurus* animal records.

Model	Observed[1]	Predicted[1]	RMSPE[1], %	RMSPE, MJ/d	MB[1], % MSE	SB[1], % MSE	RB[1], % MSE	CCC[1]	Overall Rank
61	10.30	10.19	16.76	1.73	0.37	4.64	94.99	0.32	1
11	10.30	10.61	16.61	1.71	3.30	0.54	96.16	0.28	2
41	10.30	10.06	18.08	1.86	1.69	13.13	85.18	0.30	3
60	10.30	10.48	16.54	1.70	1.18	0.56	98.25	0.27	4
59	10.30	10.56	16.75	1.72	2.38	1.50	96.12	0.28	5
28	10.30	10.85	17.76	1.83	9.02	4.73	86.25	0.28	6
40	10.30	10.10	17.84	1.84	1.13	11.32	87.56	0.29	7
1	10.30	9.52	19.28	1.99	15.31	11.30	73.39	0.29	8
8	10.30	10.17	19.52	2.01	0.41	25.98	73.62	0.31	9
14	10.30	10.99	19.71	2.03	11.49	18.27	70.24	0.32	10
22	10.30	11.40	18.35	1.89	33.90	29.16	36.94	0.23	11
54	10.30	11.12	18.48	1.90	18.89	1.45	79.66	0.23	12
9	10.30	9.93	19.29	1.99	3.41	20.27	76.32	0.28	13
12	10.30	9.43	18.60	1.92	20.31	1.12	78.57	0.23	14
19	10.30	9.48	18.32	1.89	18.68	0.01	81.31	0.19	15
10	10.30	9.37	18.86	1.94	22.64	0.88	76.47	0.22	16
33	10.30	9.56	19.25	1.98	13.93	8.97	77.10	0.22	17
6	10.30	9.46	22.39	2.31	13.29	28.92	57.79	0.23	18
38	10.30	9.13	22.16	2.28	26.18	15.94	57.87	0.23	19
13	10.30	9.13	20.06	2.07	31.73	0.21	68.06	0.17	20
39	10.30	9.03	23.00	2.37	28.45	17.88	53.67	0.22	21
65	10.30	8.75	22.47	2.31	44.84	1.51	53.65	0.18	22
37	10.30	9.61	19.66	2.02	11.40	9.86	78.74	0.10	23
21	10.30	8.76	22.09	2.27	45.67	0.43	53.90	0.13	24
48	10.30	8.95	21.23	2.19	38.08	1.11	60.81	0.09	25
62	10.30	8.19	26.67	2.75	58.83	2.45	38.72	0.14	26
4	10.30	13.00	32.30	3.33	66.02	7.92	26.06	0.15	27
66	10.30	12.71	28.89	2.98	65.83	1.46	32.72	0.12	28
30	10.30	12.23	25.17	2.59	55.54	0.07	44.39	0.09	29
50	10.30	8.71	23.04	2.37	44.70	0.01	55.29	0.06	30
51	10.30	8.59	23.79	2.45	48.39	0.09	51.52	0.07	31
31	10.30	8.65	23.26	2.40	47.40	2.89	49.71	0.06	32
20	10.30	8.06	27.26	2.81	63.27	0.12	36.61	0.08	33
3	10.30	9.76	18.38	1.89	8.12	--	--	0.00	34
2	10.30	7.32	33.46	3.45	74.50	1.14	24.36	0.10	35
53	10.30	13.60	36.12	3.72	78.99	0.85	20.16	0.10	36
17	10.30	13.93	40.53	4.17	75.57	7.82	16.61	0.12	37
52	10.30	7.76	30.59	3.15	64.94	2.74	32.31	0.05	38
47	10.30	8.22	26.58	2.74	57.65	3.58	38.77	0.02	39

[1]Observed= observed enteric CH_4 emissions, Predicted= predicted enteric CH_4 emissions utilizing the corresponding enteric CH_4 prediction model, RMSPE= root mean square prediction error, MB= mean bias, SB= slope bias, RB= residual bias, CCC= concordance correlation coefficient.

Model	Observed[1]	Predicted[1]	RMSPE[1], %	RMSPE, MJ/d	MB[1], % MSE	SB[1], % MSE	RB[1], % MSE	CCC[1]	Overall Rank
18	10.30	14.45	44.40	4.57	82.37	4.32	13.30	0.10	40
57	10.30	7.35	33.39	3.44	73.36	0.17	26.47	0.02	41
44	10.30	7.19	35.06	3.61	74.25	1.15	24.60	0.03	42
56	10.30	6.97	36.41	3.75	78.54	0.01	21.45	0.04	43
36	10.30	7.45	33.16	3.42	69.60	2.33	28.07	0.02	44
45	10.30	6.10	44.19	4.55	85.11	0.59	14.30	0.05	45
63	10.30	15.06	49.58	5.11	86.92	1.96	11.13	0.06	46
16	10.30	7.87	33.33	3.43	49.85	22.19	27.95	0.00	47
35	10.30	10.01	25.65	2.64	1.19	52.21	46.61	-0.11	48
58	10.30	7.26	34.28	3.53	74.12	0.05	25.83	0.01	49
5	10.30	17.01	68.44	7.05	90.59	3.62	5.79	0.05	50
46	10.30	6.89	37.38	3.85	78.34	0.00	21.66	0.01	51
43	10.30	6.22	43.23	4.45	84.05	0.04	15.92	0.02	52
15	10.30	7.15	37.49	3.86	66.58	11.36	22.06	0.01	53
42	10.30	7.09	35.80	3.69	75.79	0.24	23.98	0.00	54
23	10.30	18.33	81.10	8.35	92.59	3.28	4.14	0.04	55
25	10.30	19.29	90.84	9.35	92.34	4.36	3.31	0.04	56
29	10.30	6.23	43.47	4.48	82.38	1.20	16.42	0.00	57
26	10.30	22.19	118.71	12.22	94.62	3.47	1.91	0.03	58
24	10.30	22.59	122.77	12.64	94.62	3.59	1.79	0.02	59
49	10.30	4.92	55.38	5.70	88.85	1.90	9.25	0.01	60
27	10.30	24.14	137.11	14.12	96.13	2.39	1.48	0.02	61
32	10.30	4.12	62.46	6.43	92.11	0.00	7.89	0.00	62
64	10.30	7.40	45.13	4.65	38.96	46.23	14.82	-0.09	63
7	10.30	6.81	46.01	4.74	54.24	31.32	14.44	-0.05	64
55	10.30	5.32	51.56	5.31	88.03	1.30	10.68	0.00	65
34	10.30	3.17	71.42	7.35	93.89	0.03	6.09	0.00	66

[1]Observed= observed enteric CH_4 emissions, Predicted= predicted enteric CH_4 emissions utilizing the corresponding enteric CH_4 prediction model, RMSPE= root mean square prediction error, MB= mean bias, SB= slope bias, RB= residual bias, CCC= concordance correlation coefficient.

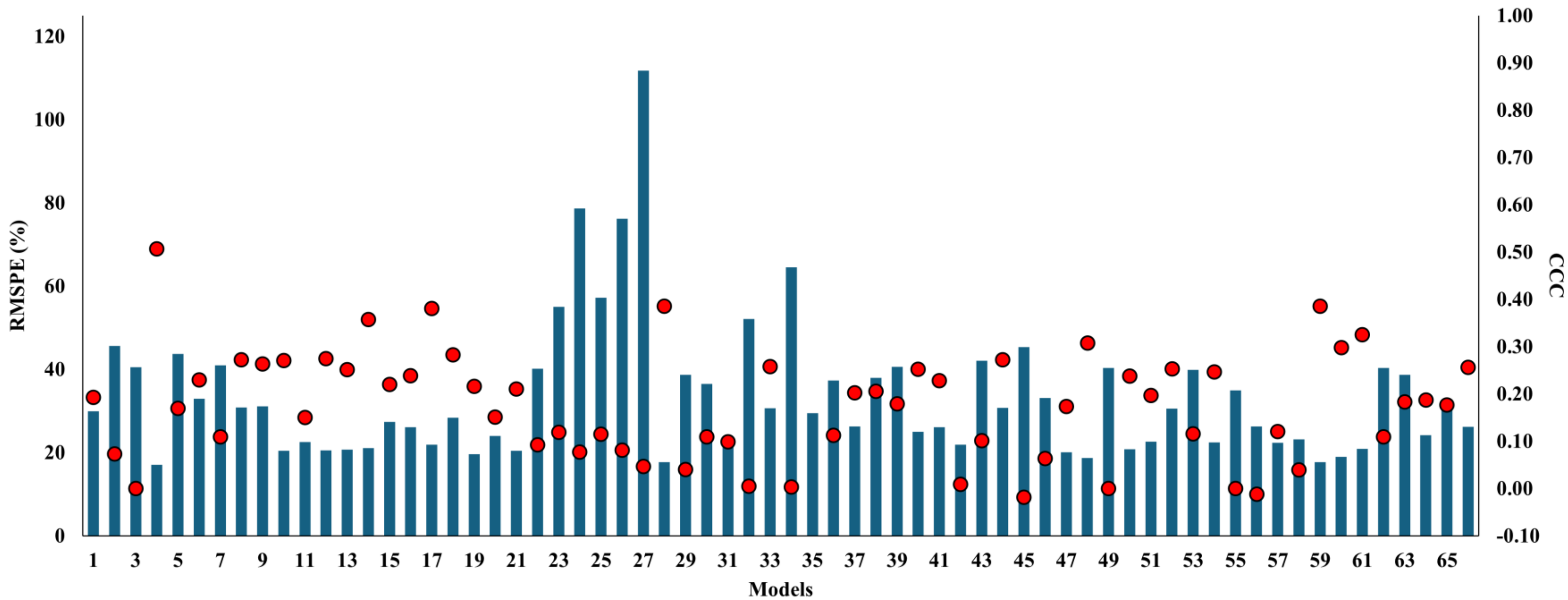

Figure 4.5. Root mean square prediction error as a percentage of the observed mean (RMSPE [%]; bars) and concordance correlation coefficient (CCC; dots) for 66 models predicting enteric methane emissions. Models were evaluated using an independent database containing 133 individual animal records from *Bos indicus* finishing beef steers fed a concentrate-based diet.

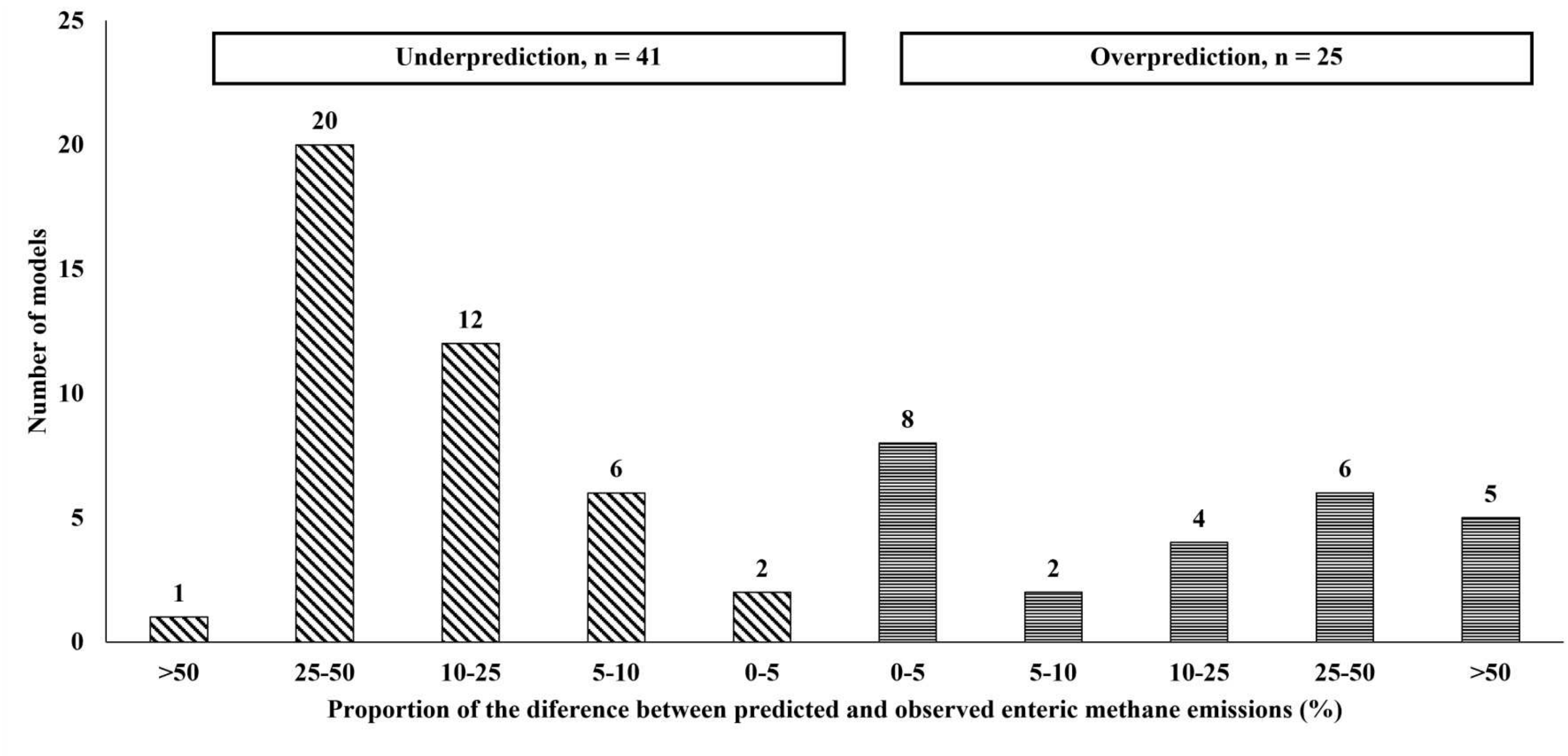

Figure 4.6. Number of models that underpredicted or overpredicted enteric CH_4 emissions, classified by the proportional difference between predicted and observed values. A total of 66 models were evaluated using an independent database containing 133 individual animal records from *Bos indicus* finishing beef steers fed a concentrate-based diet.

Table 4.12. Weighted ranking of methane prediction models based on concordance correlation coefficient, root mean square prediction error, mean bias, slope bias, and residual bias, using an independent database containing 133 individual *Bos indicus* animal records.

Model	Observed[1]	Predicted[1]	RMSPE[1], %	RMSPE, MJ/d	MB[1], % MSE	SB[1], % MSE	RB[1], % MSE	CCC[1]	Overall Rank
4	7.27	7.72	17.04	1.24	13.40	25.37	61.24	0.51	1
28	7.27	7.37	17.69	1.29	0.64	42.56	56.80	0.39	2
59	7.27	7.49	17.70	1.29	2.93	65.27	31.80	0.39	3
48	7.27	7.05	18.70	1.36	2.67	45.86	51.46	0.31	4
60	7.27	7.57	18.96	1.38	4.75	43.99	51.26	0.30	5
61	7.27	6.41	20.89	1.52	31.98	37.72	30.30	0.33	6
14	7.27	6.35	21.05	1.53	36.32	20.55	43.13	0.36	7
12	7.27	6.60	20.55	1.49	20.19	36.31	43.50	0.28	8
17	7.27	8.36	21.94	1.60	46.74	13.56	39.70	0.38	9
10	7.27	6.62	20.48	1.49	19.00	38.60	42.39	0.27	10
13	7.27	6.62	20.73	1.51	18.77	36.75	44.48	0.25	11
19	7.27	7.48	19.66	1.43	2.04	48.51	49.45	0.22	12
50	7.27	6.66	20.85	1.52	16.40	18.38	65.22	0.24	13
21	7.27	6.78	20.45	1.49	10.84	57.55	31.61	0.21	14
54	7.27	8.22	22.42	1.63	33.67	30.94	35.39	0.25	15
18	7.27	8.99	28.36	2.06	69.51	7.11	23.38	0.28	16
47	7.27	7.46	20.06	1.46	1.61	64.15	34.24	0.17	17
40	7.27	5.99	24.96	1.81	49.94	11.56	38.50	0.25	18
66	7.27	8.75	26.19	1.90	60.55	34.02	5.43	0.26	19
16	7.27	5.84	26.10	1.90	56.66	23.25	20.09	0.24	20
44	7.27	5.43	30.72	2.23	67.87	0.01	32.12	0.27	21
8	7.27	5.28	30.87	2.24	78.75	11.05	10.21	0.27	22
51	7.27	6.38	22.66	1.65	28.98	28.62	42.40	0.20	23
41	7.27	5.87	26.11	1.90	54.59	17.23	28.19	0.23	24
33	7.27	5.35	30.64	2.23	74.27	5.68	20.05	0.26	25
52	7.27	5.41	30.55	2.22	70.36	1.46	28.17	0.25	26
9	7.27	5.27	31.09	2.26	78.33	10.94	10.73	0.26	27
64	7.27	6.23	24.18	1.76	35.19	3.73	61.08	0.19	28
15	7.27	5.73	27.37	1.99	59.98	17.55	22.47	0.22	29
57	7.27	6.59	22.34	1.62	17.58	40.92	41.50	0.12	30
37	7.27	5.89	26.25	1.91	52.28	17.24	30.49	0.20	31
11	7.27	7.98	22.54	1.64	18.52	1.88	79.60	0.15	32
20	7.27	6.25	24.03	1.75	33.92	35.27	30.81	0.15	33
31	7.27	7.61	21.24	1.54	4.80	26.54	68.66	0.10	34
6	7.27	5.15	32.92	2.39	78.32	6.77	14.90	0.23	35
1	7.27	5.50	29.89	2.17	66.24	12.38	21.38	0.19	36
42	7.27	7.07	21.87	1.59	1.58	89.45	8.97	0.01	37
65	7.27	5.40	31.02	2.26	69.12	20.33	10.55	0.18	38
38	7.27	4.73	37.94	2.76	84.90	3.09	12.01	0.21	39

[1]Observed= observed enteric CH_4 emissions, Predicted= predicted enteric CH_4 emissions utilizing the corresponding enteric CH_4 prediction model, RMSPE= root mean square prediction error, MB= mean bias, SB= slope bias, RB= residual bias, CCC= concordance correlation coefficient.

Model	Observed[1]	Predicted[1]	RMSPE[1], %	RMSPE, MJ/d	MB[1], % MSE	SB[1], % MSE	RB[1], % MSE	CCC[1]	Overall Rank
58	7.27	6.60	23.22	1.69	15.75	10.20	74.05	0.04	40
63	7.27	9.89	38.73	2.82	86.29	10.33	3.38	0.18	41
39	7.27	4.51	40.63	2.95	87.19	4.41	8.41	0.18	42
36	7.27	4.89	37.34	2.72	76.93	12.73	10.34	0.11	43
30	7.27	9.53	36.46	2.65	72.53	1.12	26.34	0.11	44
53	7.27	9.89	39.92	2.90	81.30	10.41	8.29	0.12	45
56	7.27	6.27	26.26	1.91	27.37	3.85	68.78	-0.01	46
5	7.27	10.27	43.70	3.18	88.79	1.80	9.41	0.17	47
46	7.27	5.38	33.15	2.41	61.89	1.78	36.33	0.06	48
35	7.27	7.59	29.49	2.14	2.16	44.49	53.35	-0.14	49
62	7.27	4.63	40.37	2.94	81.04	8.04	10.91	0.11	50
22	7.27	9.87	40.12	2.92	79.29	9.87	10.84	0.09	51
7	7.27	4.58	41.02	2.98	81.34	4.37	14.29	0.11	52
23	7.27	11.13	54.98	4.00	93.15	0.97	5.88	0.12	53
29	7.27	4.88	38.68	2.81	72.27	19.97	7.76	0.04	54
43	7.27	4.49	42.08	3.06	82.39	5.98	11.63	0.10	55
55	7.27	5.28	34.98	2.54	61.17	--	--	0.00	56
25	7.27	11.29	57.18	4.16	93.60	0.55	5.84	0.12	57
2	7.27	4.23	45.62	3.32	83.92	6.90	9.18	0.07	58
3	7.27	9.76	40.55	2.95	71.11	--	--	0.00	59
26	7.27	12.73	76.22	5.54	96.89	0.12	2.99	0.08	60
49	7.27	4.80	40.32	2.93	70.77	--	--	--	61
24	7.27	12.91	78.65	5.72	97.07	0.08	2.85	0.08	62
32	7.27	3.82	52.14	3.79	83.02	10.43	6.54	0.01	63
27	7.27	15.36	111.81	8.13	99.07	0.09	0.84	0.05	64
45	7.27	4.56	45.34	3.30	67.53	9.46	23.01	-0.02	65
34	7.27	2.85	64.49	4.69	88.90	6.82	4.28	0.00	66

[1]Observed= observed enteric CH_4 emissions, Predicted= predicted enteric CH_4 emissions utilizing the corresponding enteric CH_4 prediction model, RMSPE= root mean square prediction error, MB= mean bias, SB= slope bias, RB= residual bias, CCC= concordance correlation coefficient.

Table 4.13. Seven methane prediction model aggregations generated based on model evaluation rank using an independent database containing 888 individual animal records, including the aggregation methodology utilized by the Beef Cattle Nutrient Requirements Model.

Aggregation	Models Utilized
A1	Top model (61)
A2	Top 3 models (61, 40, 59)
A3	Top 5 models (61, 40, 59, 60, 28)
A4	Top 9 models (61, 40, 59, 60, 28, 41, 14, 11, 8)
A5	Top 25% of models (rank 1-17)
A6	Top 50% of models (rank 1-33)
A7	All models (rank 1-66)
NASEM	Model aggregation utilized by the Beef Cattle Nutrient Requirements Model (NASEM, 2016; low-forage): 2, 16, 33, 61, 62

Table 4.14. Seven methane prediction model aggregations generated based on model evaluation rank using an independent database containing 755 individual *Bos taurus* animal records, including the aggregation methodology utilized by the Beef Cattle Nutrient Requirements Model.

Aggregation	Models Utilized
A1	Top model (61)
A2	Top 3 models (61, 11, 41)
A3	Top 5 models (61, 11, 41, 60, 59)
A4	Top 9 models (61, 11, 41, 60, 59, 28, 40, 1, 8)
A5	Top 25% of models (rank 1-17)
A6	Top 50% of models (rank 1-33)
A7	All models (rank 1-66)
NASEM	Model aggregation utilized by the Beef Cattle Nutrient Requirements Model (NASEM, 2016; low-forage): 2, 16, 33, 61, 62

Table 4.15. Seven methane prediction model aggregations generated based on model evaluation rank using an independent database containing 133 individual *Bos indicus* animal records, including the aggregation methodology utilized by the Beef Cattle Nutrient Requirements Model.

Aggregation	Models Utilized
A1	Top model (4)
A2	Top 3 models (4, 28, 59)
A3	Top 5 models (4, 28, 59, 48, 60)
A4	Top 9 models (4, 28, 59, 48, 60, 61, 14, 12, 17)
A5	Top 25% of models (rank 1-17)
A6	Top 50% of models (rank 1-33)
A7	All models (rank 1-66)
NASEM	Model aggregation utilized by the Beef Cattle Nutrient Requirements Model (NASEM, 2016; low-forage): 2, 16, 33, 61, 62

Table 4.16. Model evaluation of aggregated methane prediction models using an independent database containing 888 individual animal records from finishing steers fed a concentrate-based diet.

Aggregation Method	Observed[1]	Predicted[1]	RMSPE[1], %	RMSPE, MJ/d	MB[1], % MSE	SB[1], % MSE	RB[1], % MSE	CCC[1]
NASEM	9.84	8.13	23.68	2.33	54.17	0.02	45.81	0.40
A1	9.84	9.63	15.99	1.57	1.91	0.94	97.15	0.63
A2	9.84	9.74	16.08	1.58	0.44	0.75	98.81	0.62
A3	9.84	9.92	15.98	1.57	0.22	0.13	99.65	0.61
A4	9.84	9.88	16.32	1.61	0.06	2.02	97.92	0.62
A5	9.84	9.58	16.44	1.62	2.57	0.73	96.69	0.60
A6	9.84	9.41	16.63	1.64	6.92	0.01	93.07	0.58
A7	9.84	9.62	16.21	1.60	1.94	0.44	97.61	0.57

[1]Observed= observed enteric CH_4 emissions, Predicted= predicted enteric CH_4 emissions utilizing the corresponding enteric CH_4 prediction model, RMSPE= root mean square prediction error, MB= mean bias, SB= slope bias, RB= residual bias, CCC= concordance correlation coefficient. The CCC is evaluated according to the classification suggested by Proctor et al. (2024), where values <0 indicate no agreement, 0-0.39 slight agreement, 0.40-0.59 moderate agreement, 0.60-0.80 adequate agreement, and >0.80 excellent agreement.

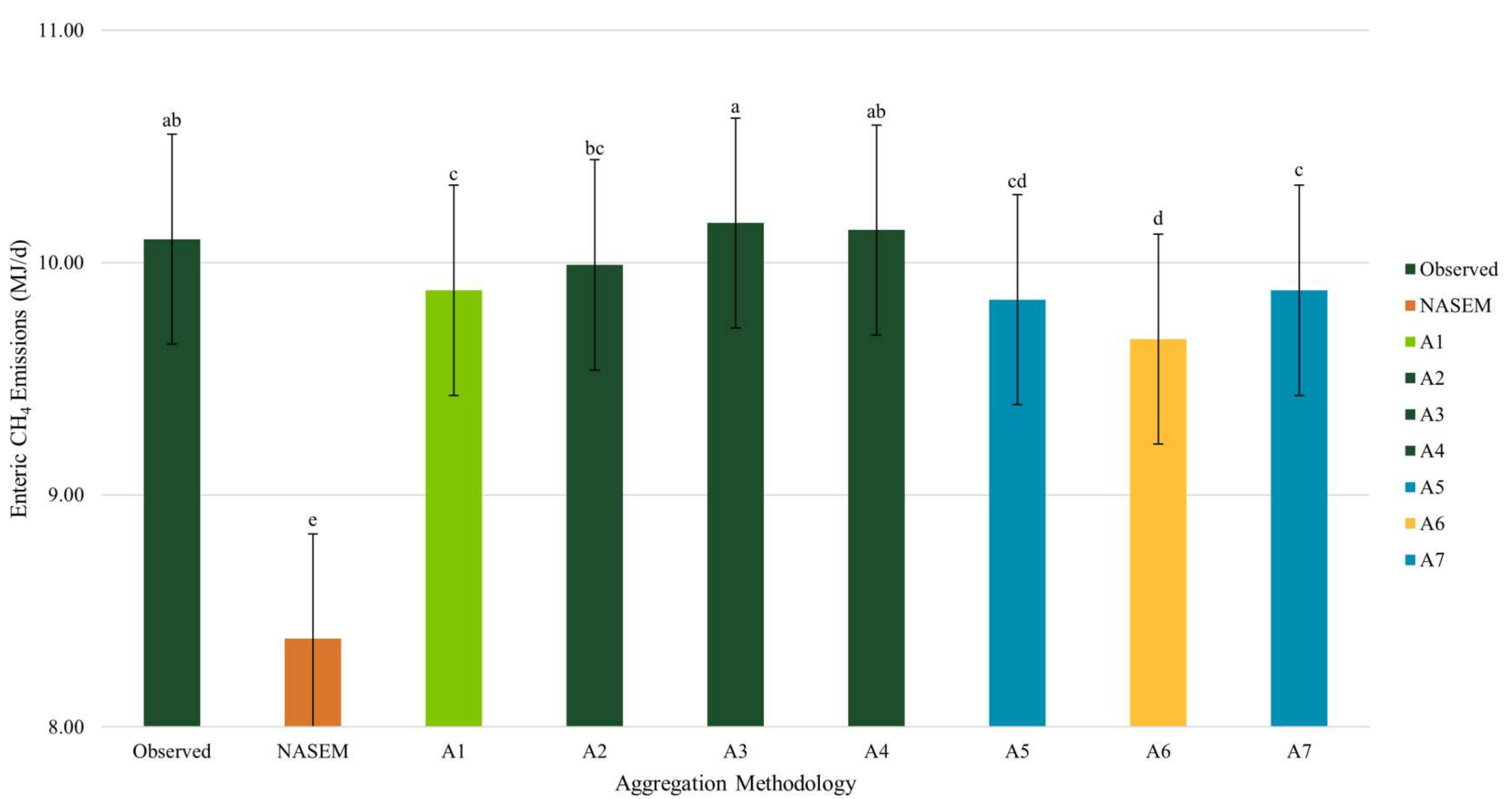

Figure 4.7. Comparison of mean enteric CH_4 emissions among model aggregation methodologies. Means followed by a common letter are not significantly different ($P > 0.05$). Analyses were conducted using an independent database containing 888 individual records from finishing beef steers fed a concentrate-based diet.

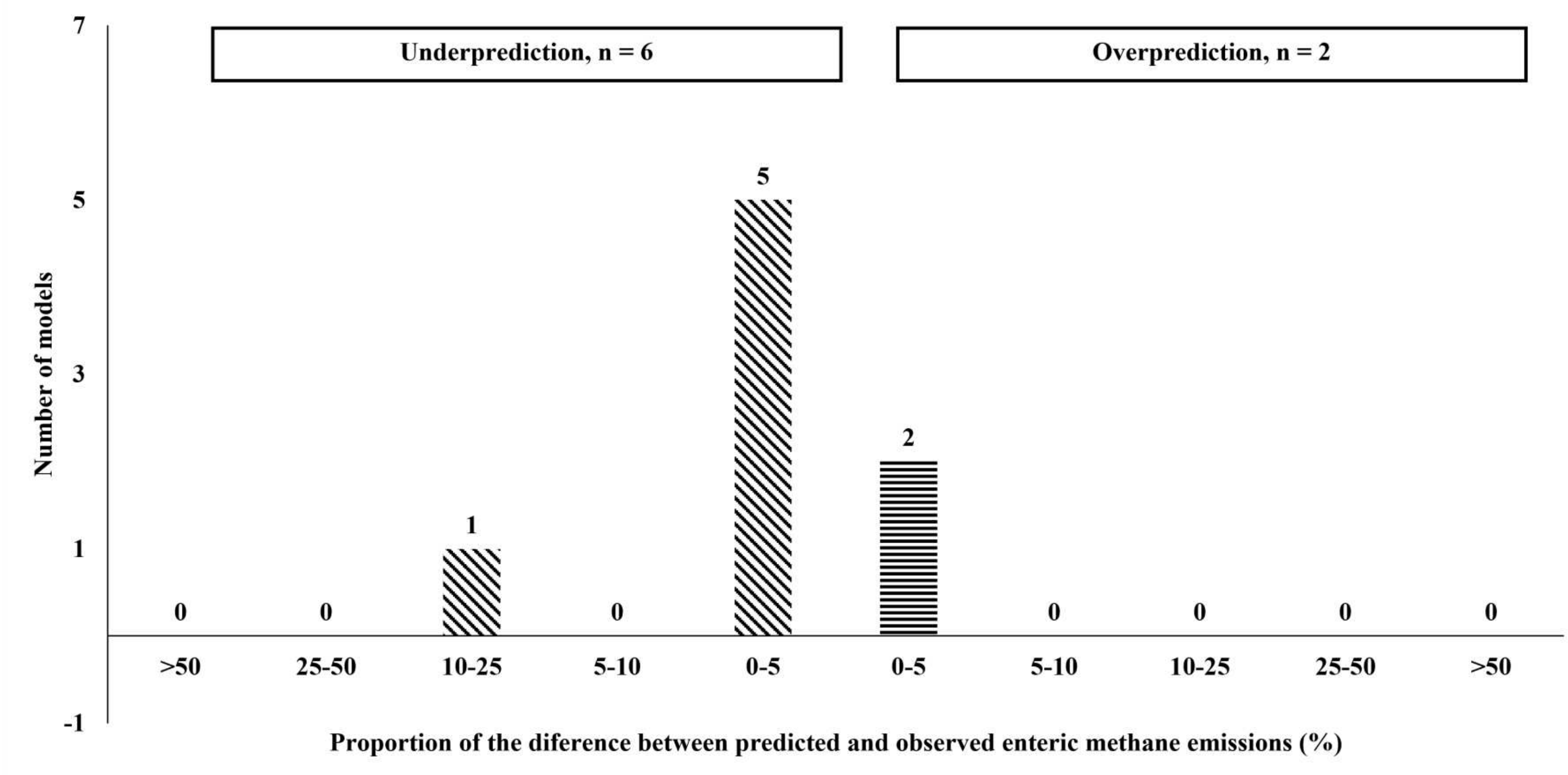

Figure 4.8. Model aggregations that underpredicted or overpredicted enteric CH_4 emissions, classified by the proportional difference between predicted and observed values, using an independent database containing 888 individual records from finishing beef steers fed a concentrate-based diet.

Table 4.17. Model evaluation of aggregated methane prediction models using an independent database containing 755 individual animal records from *Bos taurus* finishing steers fed a concentrate-based diet.

Aggregation Method	Observed[1]	Predicted[1]	RMSPE[1], %	RMSPE, MJ/d	MB[1], % MSE	SB[1], % MSE	RB[1], % MSE	CCC[1]
NASEM	10.30	8.63	23.43	2.41	47.87	1.48	50.65	0.15
A1	10.30	10.19	16.76	1.73	0.37	4.64	94.99	0.32
A2	10.30	10.29	16.81	1.73	0.00	4.45	95.54	0.31
A3	10.30	10.38	16.65	1.71	0.23	2.65	97.11	0.30
A4	10.30	10.28	17.07	1.76	0.01	6.50	93.49	0.31
A5	10.30	10.23	16.82	1.73	0.17	4.08	95.75	0.30
A6	10.30	9.90	17.21	1.77	4.95	2.64	92.41	0.27
A7	10.30	10.09	16.85	1.73	1.43	1.55	97.02	0.25

[1]Observed= observed enteric CH_4 emissions, Predicted= predicted enteric CH_4 emissions utilizing the corresponding enteric CH_4 prediction model, RMSPE= root mean square prediction error, MB= mean bias, SB= slope bias, RB= residual bias, CCC= concordance correlation coefficient. The CCC is evaluated according to the classification suggested by Proctor et al. (2024), where values <0 indicate no agreement, 0-0.39 slight agreement, 0.40-0.59 moderate agreement, 0.60-0.80 adequate agreement, and >0.80 excellent agreement.

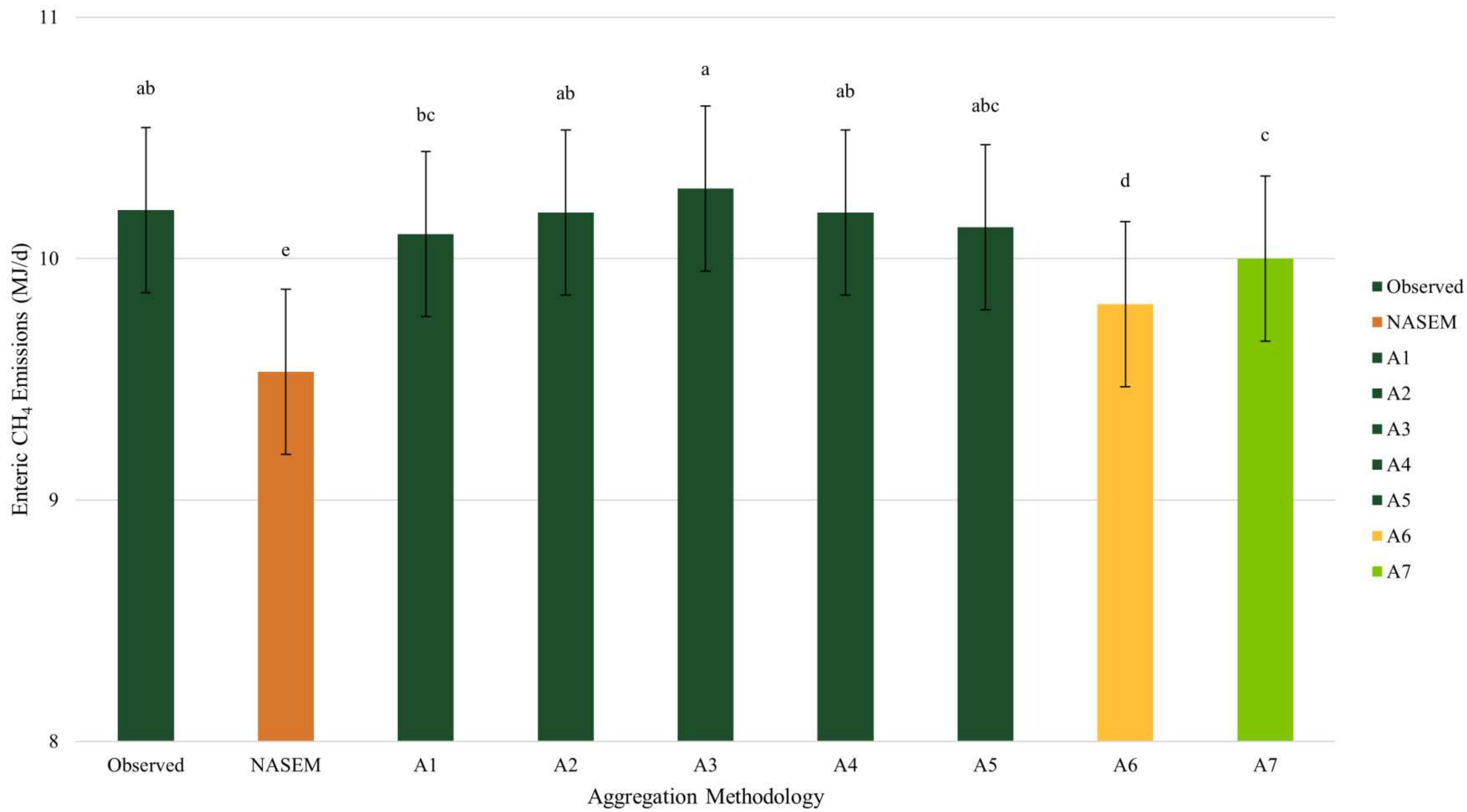

Figure 4.9. Comparison of mean enteric CH_4 emissions among model aggregation methodologies. Means followed by a common letter are not significantly different ($P > 0.05$). Analyses were conducted using an independent database containing 755 individual records from *Bos taurus* finishing beef steers fed a concentrate-based diet.

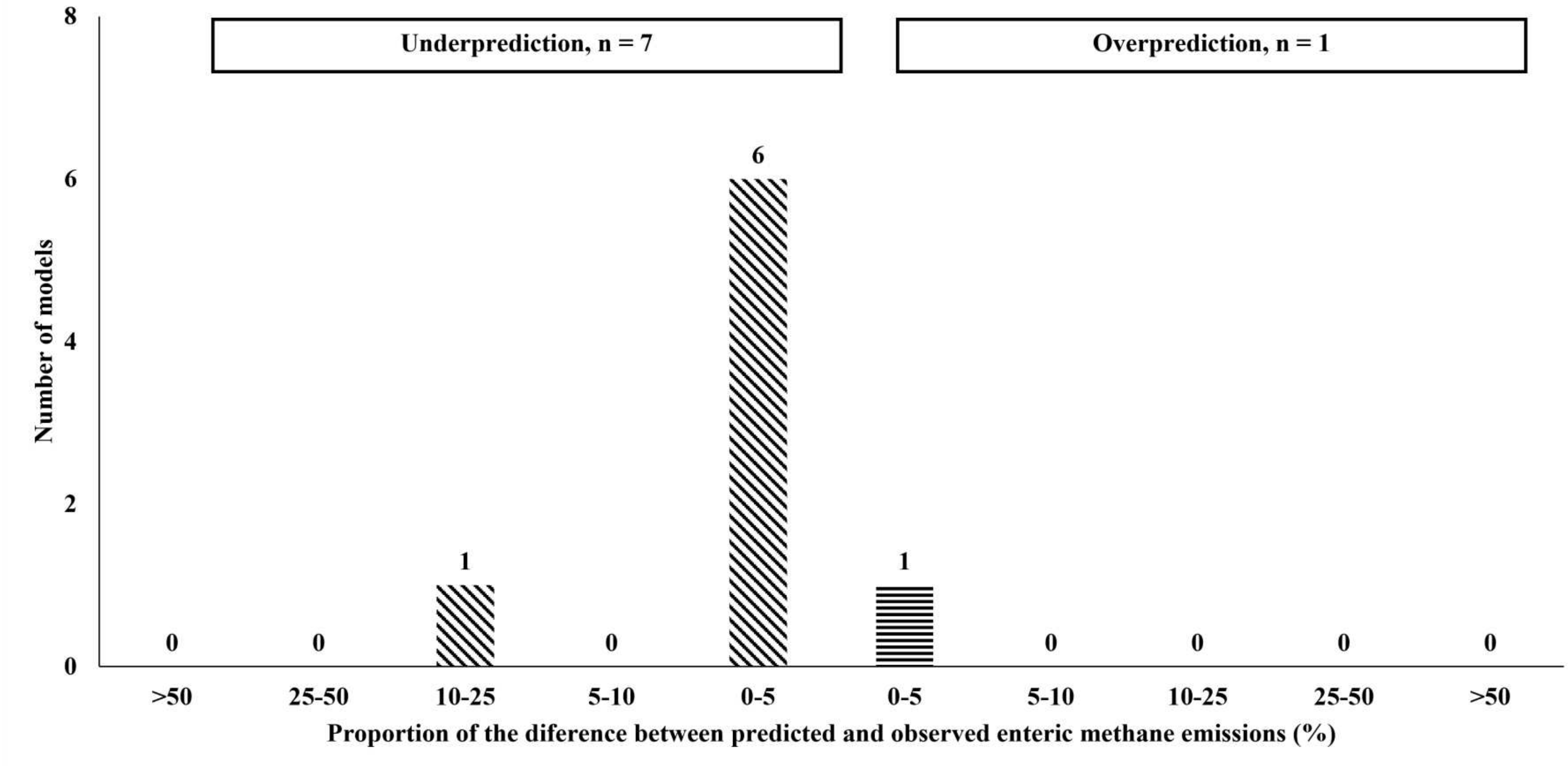

Figure 4.10. Model aggregations that underpredicted or overpredicted enteric CH_4 emissions, classified by the proportional difference between predicted and observed values, using an independent database containing 755 individual records from *Bos taurus* finishing beef steers fed a concentrate-based diet.

Table 4.18. Model evaluation of aggregated methane prediction models using an independent database containing 133 individual animal records from *Bos indicus* finishing steers fed a concentrate-based diet.

Aggregation Method	Observed[1]	Predicted[1]	RMSPE[1], %	RMSPE, MJ/d	MB[1], % MSE	SB[1], % MSE	RB[1], % MSE	CCC[1]
NASEM	7.27	5.29	32.11	2.33	71.77	13.17	15.06	0.18
A1	7.27	7.72	17.04	1.24	13.40	25.37	61.24	0.51
A2	7.27	7.53	17.27	1.26	4.25	44.91	50.83	0.44
A3	7.27	7.44	17.67	1.29	1.77	47.03	51.20	0.39
A4	7.27	7.21	17.32	1.26	0.20	43.85	55.95	0.41
A5	7.27	7.28	17.87	1.30	0.00	44.76	55.24	0.37
A6	7.27	6.73	18.98	1.38	15.53	47.16	37.31	0.36
A7	7.27	6.96	18.11	1.32	5.54	47.44	47.02	0.37

[1]Observed= observed enteric CH_4 emissions, Predicted= predicted enteric CH_4 emissions utilizing the corresponding enteric CH_4 prediction model, RMSPE= root mean square prediction error, MB= mean bias, SB= slope bias, RB= residual bias, CCC= concordance correlation coefficient. The CCC is evaluated according to the classification suggested by Proctor et al. (2024), where values <0 indicate no agreement, 0-0.39 slight agreement, 0.40-0.59 moderate agreement, 0.60-0.80 adequate agreement, and >0.80 excellent agreement.

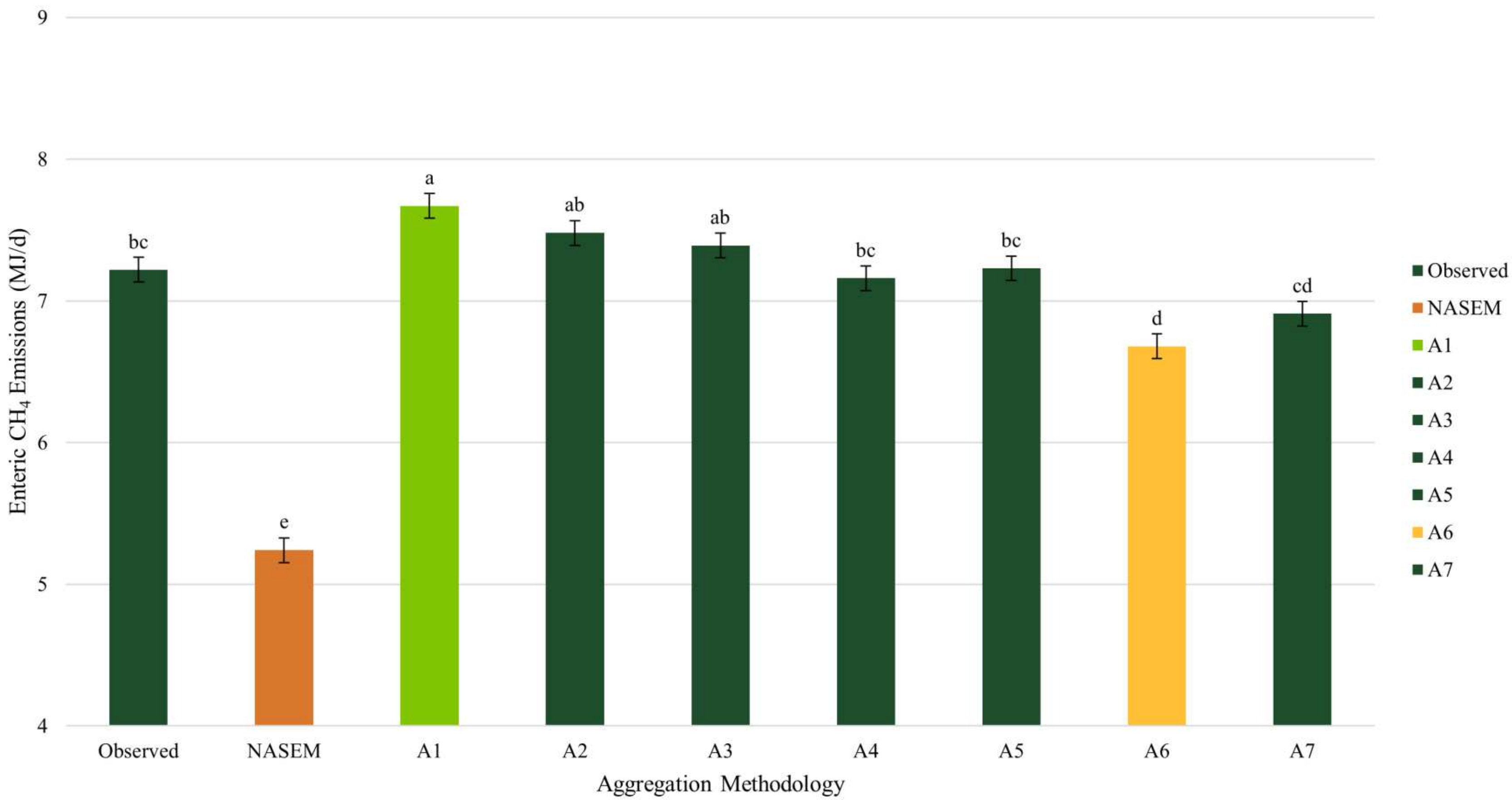

Figure 4.11. Comparison of mean enteric CH_4 emissions among model aggregation methodologies. Means followed by a common letter are not significantly different ($P > 0.05$). Analyses were conducted using an independent database containing 133 individual records from *Bos indicus* finishing beef steers fed a concentrate-based diet.

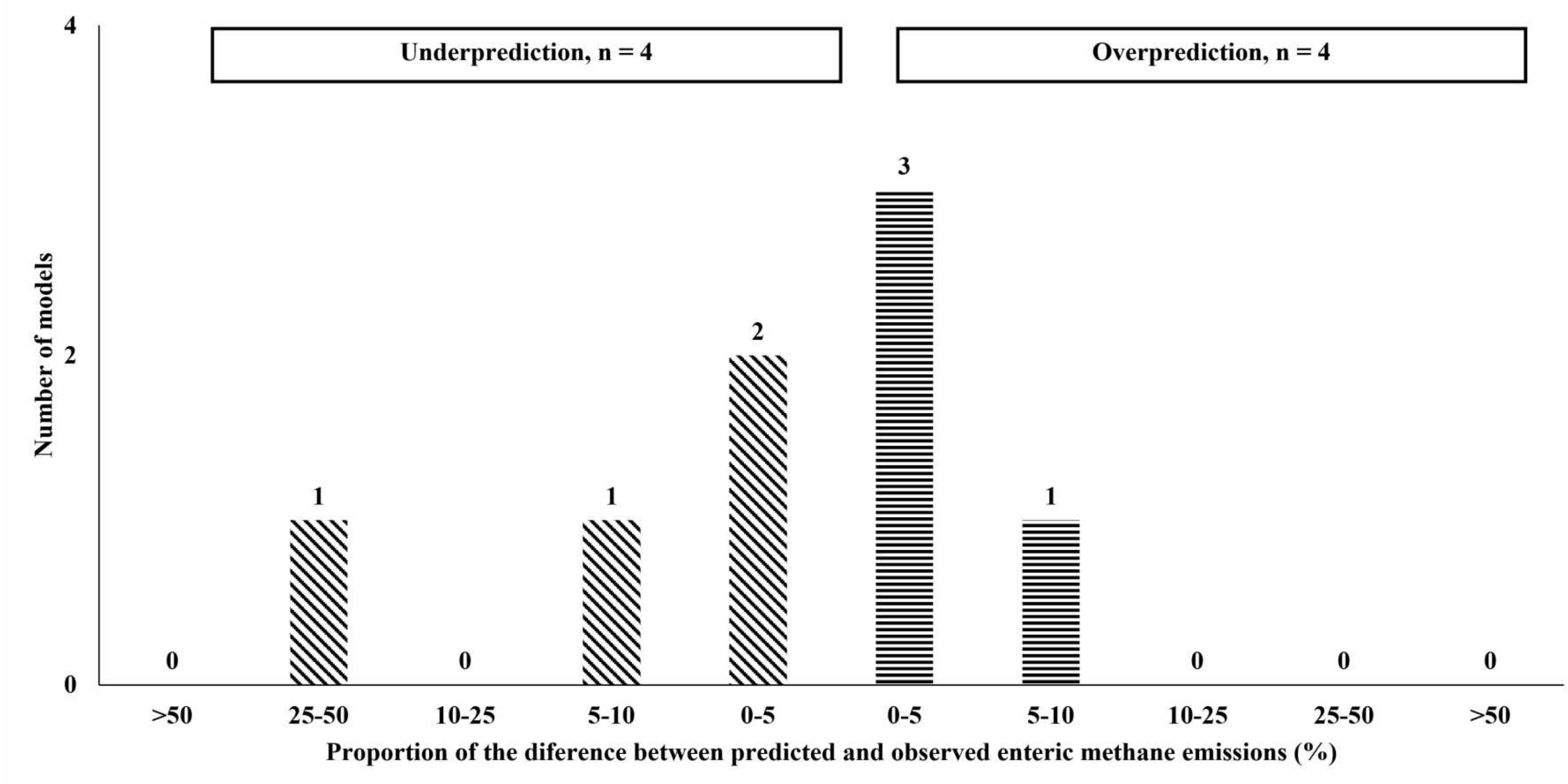

Figure 4.12. Model aggregations that underpredicted or overpredicted enteric CH_4 emissions, classified by the proportional difference between predicted and observed values, using an independent database containing 133 individual records from *Bos indicus* finishing beef steers fed a concentrate-based diet.

CHAPTER 5- TECHNICAL SUMMARY

INTRODUCTION

Mitigating greenhouse gas (GHG) emissions from beef cattle production systems while maintaining, and ideally improving, productivity represents a pressing challenge facing global agriculture. As of 2022, cattle remained the primary source of enteric methane (CH_4) emissions in the United States; however, this emissions source is inherently linked to the biological processes that enable ruminants to convert human-inedible feedstuffs into high-quality protein. Therefore, identifying and scaling innovations to further enhance the sustainability of beef production requires a systems-based, location-specific understanding of the numerous factors (*e.g.*, biological, nutritional, management, etc.) that influence both animal performance and enteric CH_4 emissions, as well as robust tools to accurately quantify these emissions. The present dissertation addresses these needs through an integrated evaluation of cattle sub-species, growth-promoting technologies (GPT), and the accuracy of enteric CH_4 prediction models in confined beef production systems.

IMPORTANCE AND APPLICATION OF RESEARCH

A central contribution of this research is improved baseline data collection that incorporated diversity in cattle type and management via the direct comparison of *Bos indicus* and *Bos taurus* cattle under controlled finishing conditions managed with and without the use of GPT. Across experiments conducted in both summer and winter environments, consistent differences in growth performance, carcass characteristics, and CH_4 emissions were observed between sub-species. *Bos taurus* cattle exhibited greater dry matter intake (DMI), average daily gain (ADG), feed efficiency (G:F), and superior carcass quality evident by a greater proportion of USDA Prime and Choice quality grades, aligning with their widespread use and history of continuous genetic improvement in U.S. feedlot systems. In contrast, *Bos indicus* cattle were observed to have lesser absolute CH_4 emissions, reflecting differences in DMI. When CH_4 emissions were expressed per unit of gain, CH_4 emissions intensity (g CH_4/kg ADG or carcass gain) was reduced when GPT was utilized. These observations underscore the importance of metric selection when quantifying enteric CH_4 emissions from beef cattle production systems and highlight tradeoffs that can exist between productivity and environmental impact by quantifying CH_4 emissions relative to resource utilization and/or beef produced.

The use of GPT further influenced both performance and emissions outcomes, reinforcing their role as a key lever for improving production efficiency. Across sub-species, GPT increased ADG, final body weight, and feed efficiency, while reducing CH_4 emissions intensity (*i.e.*, emissions per unit of gain or carcass output). Notably, interactions between sub-species and GPT indicated that the magnitude of response was not uniform, suggesting that biological differences influence how cattle respond to management interventions. These results contribute to a growing body of evidence that improving animal productivity is one of the most effective strategies for reducing CH_4 emissions intensity, CH_4 emissions per unit of production, in beef systems.

Beyond field-based experiments that are essential to baseline data collection, a major contribution of this dissertation is the comprehensive evaluation of CH_4 prediction models. By compiling a large, independent database of finishing beef cattle (n = 888) across multiple experiments, this research provides a robust platform for assessing the accuracy and precision of 66 published CH_4 prediction equations. Model performance varied widely, with many models exhibiting substantial prediction error, bias, and only slight to moderate agreement with observed emissions. These observations highlight a critical limitation in current approaches to estimating enteric CH_4, particularly when models developed under specific conditions are applied more broadly.

Importantly, this research demonstrated that model aggregation- utilizing multiple prediction models, as opposed to a single prediction model- can substantially improve predictive performance. Aggregated models consistently reduced root mean square prediction error (RMSPE) and produced estimates within ±10% of the observed mean CH_4 emissions across the three databases utilized. This approach offers a pragmatic strategy to enhance predictive performance, while continued measurement and model development remain critical for robust greenhouse gas quantification and mitigation in beef production systems. However, despite these improvements, slight to adequate concordance indicates that further refinement is necessary, particularly for predicting emissions at the individual-animal level and within underrepresented populations, such as *Bos indicus* cattle, which limits the global and commercial applicability current enteric CH_4 prediction models.

Collectively, the observations of this dissertation have important implications for beef production system resiliency, quantification of environmental impacts, and policy development. From a production standpoint, as the climate changes resulting in greater variability in temperature and precipitation extremes, the results presented in this dissertation provide empirical evidence to guide decisions regarding breed selection and the use of GPT, enabling producers to better balance performance objectives with environmental considerations. From an environmental perspective, the research highlights the need for careful interpretation of CH_4 metrics and reinforces the importance of utilizing emissions intensity, CH_4 emissions per unit of production, as a metric to balance production and environmental considerations. From a modeling standpoint, the demonstrated benefits of aggregation approaches provide an immediately applicable tool for improving greenhouse gas inventories, life cycle assessments, and sustainability benchmarking efforts while continued measurement and model development are ongoing.

ALIGNMENT WITH CSU AGNEXT STRATEGIC PRIORITIES

This research directly aligns with the AgNext strategic priority of establishing more accurate and representative baseline enteric CH_4 emissions as a foundational step toward improving enteric CH_4 prediction models and ultimately CH_4 quantification and reporting at the commercial scale. A critical limitation in current CH_4 modeling efforts is the lack of diverse, high-quality, standardized datasets derived from direct measurement enteric CH_4 emissions under commercially relevant conditions. By generating individual-animal enteric CH_4 emissions data across multiple experiments and environmental conditions, this dissertation contributes to the development of a robust empirical foundation necessary for model development and advancement. Furthermore, the integration of these data into a large, independent database enables rigorous evaluation of existing prediction models, identifying key sources of error and bias.

The observations detailed in this dissertation demonstrate that accurate baseline measurements are essential not only for evaluating current models, but also for informing the development of future prediction models that are more accurate and precise across a diverse array of production systems. The identification of DMI as a primary driver of CH_4 prediction model performance reinforces the importance of capturing fundamental biological relationships within modeling frameworks. The use of DMI in CH_4 prediction models also highlights practical limitations that may exist when applied to non-confinement beef production systems and commercial settings where quantification of individual animal feed intake is limited. Additionally, the observed variability in model performance across cattle sub-species highlights the need for more inclusive datasets that reflect the diversity of production systems and animal types to improve commercial and global applicability of CH_4 prediction models. By addressing these knowledge gaps and needs, this research advances the scientific basis for quantifying enteric CH_4 emissions and supports the development of scientifically-rigorous, data-driven, scalable solutions for mitigating enteric CH_4 in beef production systems.

CONCLUSION

In summary, this dissertation provides a comprehensive and integrated evaluation of the biological and methodological factors influencing enteric CH_4 emissions in finishing beef cattle. By combining field-based experimentation conducted in industry-relevant environments with large-scale model evaluation, this research advances understanding of the tradeoffs between productivity and environmental impact and demonstrates the potential of model aggregation to improve CH_4 prediction, thereby establishing a strong empirical foundation for future research. These contributions are critical for continuous improvement regarding the sustainability of beef production systems and for developing accurate, science-based tools to quantify and mitigate enteric CH_4 emissions from beef cattle production systems.