

Health, performance, and greenhouse gas emissions intensity in U.S. feedlot cattle

by

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B.S., Kansas State University, 2020
M.S., West Texas A&M University, 2022

AN ABSTRACT OF A DISSERTATION

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Department of Diagnostic Medicine and Pathobiology
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Abstract

Sustainability in beef production is increasingly evaluated using greenhouse gas emissions metrics, yet environmental performance in feedlot systems is inherently linked to biological efficiency and animal health. As sustainability targets expand across the beef supply chain, there is a need for production-relevant, outcomes-based approaches that integrate routinely collected health and performance data into emissions assessments. The primary objectives of this dissertation were to: evaluate the effects of production and health metrics on greenhouse gas emissions intensity (EI) in U.S. feedlot systems; assess the environmental and economic impacts of a feed additive approved for emissions reduction; quantify associations among disease burden, mortality, growth performance, and EI using commercial-scale observational data; evaluate the effectiveness of alternative treatment strategies for bovine respiratory disease (BRD); and synthesize these findings into a systems-based framework linking animal health, production efficiency, and sustainability outcomes. A large-pen commercial feedlot trial compared cattle fed lubabegron (Experior), the first U.S. Food and Drug Administration–approved feed additive for reducing gas emissions from cattle, with cattle fed ractopamine hydrochloride (Optaflexx). Cattle fed lubabegron exhibited improved growth performance and feed efficiency, reduced dry matter intake, and heavier carcass weights relative to comparator cattle. These performance differences translated to a 6.2% reduction in estimated carbon dioxide equivalent emissions per unit of carcass weight and greater estimated net returns per animal shipped. Complementary observational research using commercial feedlot data demonstrated that higher average daily gain and improved gain-to-feed ratio were consistently associated with lower lifetime EI across diverse production conditions. However, effect magnitudes varied by sex and season, highlighting biological and management heterogeneity

inherent to commercial systems. Associations between animal health and EI also were evaluated. Increased disease burden and mortality were consistently associated with higher EI, reflecting extended days on feed, impaired feed efficiency, and the loss of productive output from invested resources. Reducing mortality from 5% to 0% was estimated to lower lifetime EI by approximately 6%, illustrating the environmental consequences of lost production. A randomized clinical trial comparing tulathromycin, tulathromycin plus ketoprofen, and tildipirosin for first treatment of naturally occurring BRD in medium-risk feedlot cattle demonstrated no significant differences in morbidity, retreatment risk, or mortality across treatment groups. These findings indicate that sustainability impacts of health interventions are context-dependent and contingent upon measurable effects on downstream performance outcomes. Across study designs, production efficiency emerged as a central driver of EI. Cattle that grow more rapidly and convert feed more efficiently require fewer biological and material inputs per unit of beef produced, thereby reducing EI. Conversely, health challenges that impair growth or result in mortality increase EI by elevating inputs relative to productive output. Importantly, this work distinguishes between total emissions and EI, demonstrating that reductions in total emissions may coincide with increased mortality or reduced productivity if evaluated without appropriate functional units. This dissertation integrates epidemiological methods, commercial production data, and emissions modeling to provide a pragmatic framework for evaluating sustainability in feedlot systems. The findings demonstrate that animal health, production efficiency, and environmental performance are tightly linked components of a single biological system. Improvements in health and growth efficiency align economic, environmental, and animal welfare objectives within commercially relevant production systems. Collectively, this work supports the conclusion that healthier, more efficient cattle are inherently more sustainable, and

that meaningful progress toward beef sustainability goals will depend on optimizing core health and production management practices rather than relying solely on stand-alone environmental interventions.

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Dedication

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Preface

The chapters included in this dissertation are formatted according to the respective journal guidelines in which they were published or intended to be published. Table and Figure numbers were modified to accommodate the designated dissertation chapter, otherwise content is unchanged from the publication. Artificial intelligence–based tools were used to support grammar, sentence structure, and clarity of expression. All intellectual content, including study design, analysis, interpretation, and conclusions, was developed independently by the author.

Chapter 1 - Introduction

Sustainability has increasingly become a prominent priority for stakeholders across the beef supply chain, with environmental targets often established at the retail and corporate level and subsequently extending downstream to packers, feedlots, and cow–calf operations.

Commitments to reduce greenhouse gas (GHG) emissions made by major food companies and industry organizations translate into expectations for measurable improvements at each stage of production, even though implementation occurs at the level of individual production systems. In practice, sustainability expectations are fulfilled through quantifiable performance outcomes.

Within feedlot systems, sustainability is closely aligned with efficiency—specifically, improving growth performance, optimizing feed utilization, and minimizing disease and mortality. These outcomes are already central objectives of feedlot management, driven by biological constraints and economic incentives. Importantly, improvements in average daily gain (ADG), gain-to-feed ratio (G:F), and animal health directly influence the amount of feed, time, and resources required to produce a unit of beef, thereby affecting GHG emissions intensity (EI) regardless of whether interventions are explicitly marketed as “sustainability” technologies. This dissertation is motivated by the need to understand how familiar performance and health metrics translate into environmental outcomes, and how changes in growth performance, feed efficiency, and animal health affect GHG emissions per unit of beef produced. To address this need, a production-systems, outcomes-based approach is applied to evaluate how measurable performance and animal health metrics translate into GHG EI within commercial beef production systems. By focusing on outcomes that are already central to feedlot decision-making, this approach aligns sustainability assessment with operational and economic realities. Despite increasing emphasis on GHG mitigation in beef production, sustainability assessments rarely integrate animal health,

performance variability, and mortality into emissions evaluation using commercial-scale production data. Consequently, environmental performance is often characterized using simplified or average-animal assumptions that fail to capture the biological and management heterogeneity inherent to commercial feedlot systems.

Sustainability in Animal Agriculture: A Systems Perspective

Sustainability in animal agriculture is best understood as a multidimensional systems concept rather than a single, fixed outcome. It is commonly framed as the balance among three pillars: environmental responsibility, economic viability, and social acceptability (de Wit et al., 1995; United Nations, 2005). Achieving these objectives simultaneously is inherently challenging, as tradeoffs among pillars are unavoidable and depend on how acceptable balances are defined and interpreted by different stakeholders (Heitschmidt et al., 1996). Importantly, no single pillar can be considered in isolation or prioritized universally over the others, as each is interdependent and contributes to the overall functioning of the production system (Stackhouse-Lawson, 2022).

Building on this perspective, Stackhouse-Lawson (2022) emphasized that real-world agricultural systems operate under overlapping biological, economic, regulatory, and social constraints, requiring sustainability outcomes to be managed jointly rather than independently. This framework highlights that sustainability outcomes emerge from how production systems manage efficiency, resource use, risk, and societal expectations simultaneously, rather than from performance within any single domain.

This systems-based interpretation is reflected in how animal agriculture organizations describe sustainability goals and performance indicators. For example, the U.S. Roundtable for Sustainable Beef has identified indicators spanning environmental, economic, and social

dimensions across the beef value chain, including water resources, GHG emissions, animal health and wellness, efficiency and yield, employee well-being, and land resources (USRSB, 2022). At a broader policy level, the United States Department of Agriculture defines sustainability as an integrated system of plant and animal production practices that satisfy food and fiber needs while enhancing environmental quality, sustaining economic viability, and improving quality of life over the long term (USDA, 2007).

Despite alignment around core principles, interpretations of what constitutes “sustainable” animal agriculture vary substantially depending on stakeholder perspectives, institutional priorities, and communication objectives (Zepeda et al., 2013). Consequently, sustainability in animal agriculture is fundamentally an outcomes-based problem, requiring evaluation of measurable production, environmental, and societal impacts rather than adherence to a specific ideology. Livestock systems operate at the intersection of biological, economic, and social processes; therefore, meaningful sustainability assessment must rely on integrated, science-based approaches that quantify outcomes across domains while acknowledging that stakeholder priorities may differ (Kebreab, 2013). Within this framework, sustainability assessment that cannot be operationalized using routinely collected production data is unlikely to meaningfully influence management decisions at scale.

In commercial beef production, sustainability must be demonstrated within the constraints of routine management and decision-making. Feedlot systems are characterized by biological variability, economic risk, and heterogeneous cattle populations, while sustainability expectations increasingly require documentation of environmental performance using information already collected for production and management purposes. As a result, sustainability assessment in feedlot systems must rely on scalable, decision-relevant metrics that

can be derived from operational data rather than intensive, site-specific inventories. These realities necessitate approaches that translate day-to-day performance and management outcomes into meaningful environmental indicators that are compatible with commercial production systems.

Sustainability in Beef Production: Emissions Intensity and Production

Efficiency

Within the broader systems-based framework of sustainability in animal agriculture, beef production warrants particular attention due to its contribution to the global protein supply and its reliance on biologically intensive production processes. As demand for animal-source protein increases under constraints on land, water, and other natural resources, scrutiny of the environmental performance of beef production systems has intensified. This scrutiny has increasingly centered on GHG emissions as a primary indicator of environmental sustainability, even though emissions alone do not fully capture the complexity of sustainability within beef production systems.

Beef production's role in global protein supply

Beef production contributes to global food security by converting feed resources that are largely unsuitable for direct human consumption into high-quality animal protein. Sustaining and expanding this protein supply will increasingly depend on production systems that improve growth efficiency, feed utilization, and time to slaughter (Greenwood, 2021).

Substantial efficiency gains in beef production have already been achieved and continue to progress. Relative to 1977 production systems, generating an equivalent quantity of beef in 2007 was associated with reductions in resource use of 33% for land, 12.1% for water, 18.6% for feed, and 30.1% for animal numbers (Capper, 2011). Management and genetic strategies that increase

biological efficiency, such as reducing age at slaughter, increasing carcass weight, maintaining heterosis, and implementing multi-trait selection indices are ways to continue achieving efficiency gains (Terry et al., 2021).

Beef production is distinct from many livestock systems in that it integrates extensive cow–calf phases with intensive feedlot finishing. Given the limited availability of land suitable for grazing, future increases in beef protein supply are expected to occur primarily through sustainable intensification driven by improvements in production efficiency, rather than expansion of extensive production systems (McAllister et al., 2020).

Growing societal and policy focus on greenhouse gas emissions

As concerns about climate change have intensified, societal, corporate, and policy attention has increasingly focused on GHG emissions from livestock systems, alongside broader concerns about food production (Thompson et al., 2025). Within this context, mitigation efforts in ruminant production have centered largely on enteric methane (CH₄) emissions, reflecting CH₄'s high global warming potential and its prominence within cattle production systems (Thompson et al., 2025).

International climate commitments, including initiatives following the Paris Climate Accord such as the Global Methane Pledge, have further elevated attention on agricultural CH₄ emissions, with targets to reduce global CH₄ emissions by at least 30% by 2030 relative to a 2020 baseline (Thompson et al., 2025). Consistent with this focus, enteric CH₄ accounts for approximately 5% of global anthropogenic GHG emissions and 27% of anthropogenic CH₄ emissions, according to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Dhakal et al., 2023). In the United States specifically, enteric CH₄ from beef and dairy

cattle represented approximately 2.2% and 0.8% of total GHG emissions in 2024, respectively, based on inventories reported by the U.S. Environmental Protection Agency (EPA, 2024).

In response, industry-led sustainability initiatives have incorporated emissions reduction targets alongside productivity goals. For example, the U.S. Roundtable for Sustainable Beef has outlined a pathway for the U.S. beef supply chain to achieve climate neutrality by 2040, including a 10% reduction in GHG emissions per pound of beef produced in the feedlot sector by 2030 (USRSB, 2022). Climate neutrality is defined as balancing total GHG emissions with GHG removals such that the system has no net contribution to additional warming, as evaluated using life cycle assessment (LCA) approaches and subject to assumptions regarding methane accounting and carbon sequestration (Thompson et al., 2025). Accordingly, the extent to which this goal is attainable depends on these underlying methodological choices, particularly how CH₄ emissions are characterized and the magnitude and persistence of carbon sequestration, which remain areas of uncertainty (Thompson et al., 2025).

Together, these international commitments, emissions benchmarks, and industry initiatives have placed beef production systems under increasing scrutiny with respect to their GHG emissions.

Distinction between total emissions and emissions intensity

Greenhouse gas emissions from beef production systems may be expressed as either total emissions or EI per unit of beef produced, and interpretations of environmental performance depend strongly on the metric selected (McAtee et al., 2025). Total emissions represent the absolute quantity of GHGs emitted by a group of animals or an entire production system and are particularly relevant for national inventories, regulatory reporting, and policy evaluation. However, reliance on total emissions alone can be misleading when assessing production efficiency or the effects of management practices (McAtee et al., 2025).

In contrast, EI is commonly expressed as kilograms of carbon dioxide equivalents (CO₂e) per kilogram of final body weight or beef produced and quantifies emissions relative to productive

output (McAtee et al., 2025). This metric more directly reflects the efficiency with which biological and material inputs are converted into edible protein. Prior work has shown that increases in animal mortality may reduce total emissions during the finishing phase simply because fewer animals complete the feeding period, while simultaneously increasing lifetime emissions per unit of beef produced due to lost productive output and wasted invested resources (McAtee et al., 2025). Careful interpretation of emissions metrics is therefore required, particularly in contexts where reductions in total emissions may coincide with increased animal mortality or reduced productive output.

Efficiency as the link between production and environmental outcomes

In beef production systems, GHG emissions are inseparable from production efficiency. Emissions are an unavoidable consequence of the biological processes required to produce beef, and their environmental impact is inherently linked to the quantity of usable product generated. Improvements in growth rate, feed efficiency, and time to slaughter increase beef output while distributing emissions across greater productive gain, thereby reducing EI.

Accordingly, production efficiency represents the critical link between the economic and environmental dimensions of sustainability in beef production systems. Evaluating emissions on a per unit of production basis aligns environmental performance with the fundamental objective of beef production and provides a framework for assessing how management practices, animal health outcomes, and technological interventions influence sustainability outcomes across the production system.

How Greenhouse Gas Emissions Are Estimated in Beef Systems

Life Cycle Assessment Approaches

Life cycle assessment (LCA) is a commonly used framework for quantifying GHG emissions from beef production systems (Lupo et al., 2014; Stackhouse-Lawson et al., 2012; Beauchemin et al., 2010). Life cycle assessment is a standardized methodology that defines system boundaries, compiles an inventory of relevant inputs and outputs, and evaluates environmental impacts across defined production stages, typically from birth to departure from the system, or cradle to gate (International Organization for Standardization, 2006).

Although numerous LCAs have been conducted across a range of beef production systems, direct comparison among studies is often limited by differences in system boundaries, functional units, data sources, and modeling assumptions, resulting in substantial variability in reported emissions estimates (Werth et al., 2021). Despite these challenges, LCAs are valuable for identifying stages or processes within beef production systems that contribute disproportionately to environmental impacts and for evaluating potential mitigation strategies (Lupo et al., 2014).

Management practices in beef cattle production vary widely by region due to differences in climate, feed resources, and production systems, making regional specificity an important consideration in LCA modeling (Lupo et al., 2014). Beef production LCAs have been conducted in multiple countries, including Japan, Ireland, Australia, Canada, Sweden, and the United States, using both whole system LCA and systems modeling approaches (Cederberg and Stadig, 2003; Ogino et al., 2004; Casey and Holden, 2006a; Peters et al., 2010; Pelletier et al., 2010; Beauchemin et al., 2010; Foley et al., 2011; Johnson et al., 2003). Within the United States, regionally focused LCAs have been completed for beef production systems in California

(Stackhouse-Lawson et al., 2012) and the Northern Great Plains (North Dakota, South Dakota, and Nebraska; Lupo et al., 2014).

While whole system LCAs provide a comprehensive framework for estimating emissions and identifying major contributors to environmental impact, results remain sensitive to underlying assumptions and emission factors, which can complicate comparisons across models and studies (Lupo et al., 2014).

Practical Emissions Calculators Used in Industry

In addition to formal life cycle assessments, GHG emissions in beef production are increasingly estimated using industry-facing emissions calculators designed to translate routinely collected operational production data into standardized emissions metrics. These tools are typically deterministic in nature, relying on established emission factors and published methodologies rather than site-specific life cycle inventories, and are intended to support benchmarking and decision-making within commercial production systems (Elanco, 2023).

One example of such a tool is UpLook 1.0, an emissions estimation platform developed by Elanco Animal Health. UpLook 1.0 integrates emissions calculation methodologies derived from guidance provided by the U.S. Department of Agriculture, the Intergovernmental Panel on Climate Change, and the U.S. Environmental Protection Agency, with emissions expressed as CO₂e (Dong et al., 2019; USDA, 2014; EPA, 2022; Elanco, 2023). Emissions estimates are generated using routinely collected feedlot operational data, including animal performance, feeding duration, and management inputs, rather than comprehensive, site-specific life cycle inventories (Elanco, 2023; Horton et al., 2023; McAtee et al., 2024).

In parallel, academic institutions have developed applied emissions calculators to support phase-specific evaluation of beef production systems. For example, Kansas State University has

developed two GHG emissions calculators to quantify direct emissions from enteric CH₄ and manure management during the stocker and feedlot phases of beef production. These tools rely on operational production data and standardized emission factors to estimate EI within defined production phases. A detailed description of the methodological framework applied in this dissertation is provided in Chapter 5.

Collectively, industry-facing and academically developed emissions calculators provide a practical framework for evaluating GHG EI within commercial beef systems. While these tools do not replace full LCA, they enable consistent and data-driven evaluation of how performance and management influence emissions outcomes using information that producers already collect. Rather than producing absolute emissions inventories, this dissertation emphasizes comparative evaluations of EI using routinely collected production data to assess the sustainability implications of management and health decisions.

Estimation of GHG emissions in commercial beef production systems necessarily involves methodological assumptions and inherent limitations. Direct measurement of emissions at the scale of individual feedlots or across large commercial populations is not currently feasible. As a result, emissions estimates must rely on models and calculators that apply standardized emission factors to operational production data, and are sensitive to the selection of system boundaries, functional units, and underlying assumptions. In this dissertation, emissions are expressed as kg CO₂e per unit of beef produced, or EI, because this functional unit most directly aligns environmental outcomes with production objectives and avoids interpretive challenges associated with total emissions estimates. Importantly, the emissions calculators used here are intended as decision-support tools that enable comparative evaluation across

management strategies and production conditions, rather than as precise measures of absolute emissions.

Production Efficiency as a Central Driver of Emissions Intensity

One of the most effective strategies for decreasing EI is improving growth performance (Boadi et al., 2004; Monteny et al., 2006; Capper and Hayes, 2012; Stackhouse et al., 2012). Improvements in ADG and G:F are consistently associated with lower EI, reflecting more efficient use of biological and feed resources. Feedlot cattle that gain weight more efficiently require less feed per unit of weight gain, which reduces enteric CH₄ emissions on a per unit of production basis (Coopridge et al., 2011; Min et al., 2022; McAtee et al., 2025). The feedlot phase is particularly influential in this context, as it contributes approximately 20% of lifetime GHG emissions while accounting for 41.8% of total lifetime body weight gain (McAtee et al., 2025). This disproportionate contribution to productive output highlights the critical role of feedlot performance in improving production efficiency and reducing EI (McAtee et al., 2025).

Animal Health as a Constraint on Sustainability

Animal health is central to sustainability in livestock systems. Globally, disease is estimated to reduce animal protein output by more than 20% annually (World Organisation for Animal Health, 2008). Diseases such as bovine respiratory disease (BRD), coccidiosis, and lameness conditions, including foot rot, impair cattle growth and feed efficiency, contributing to economic inefficiencies and broader sustainability challenges across livestock production systems (Husu-Kallio, 2008; Cervantes, 2015; Sneeringer et al., 2015). Disease related reductions in productivity decrease meat yield and increase feed costs per unit of product, as feed inputs are distributed across fewer output units. In addition, prolonged time to reach finishing weight increases total feed use and reduces ADG, further diminishing production efficiency.

Increased animal mortality has particularly important implications for sustainability, as resources invested in animal maintenance and growth are not offset by productive output or sale (Capper, 2020). Cattle health is closely linked to feeding behavior and performance, with declines in dry matter intake (DMI) representing a consistent biological response among calves exhibiting clinical signs of illness (Krehbiel, 2020). Reduced intake contributes to slower growth and poorer feed efficiency, reinforcing the negative effects of disease on production performance. Collectively, these biological responses link animal health directly to productivity and environmental performance in beef production systems. Reducing disease burden and minimizing mortality improve overall herd health and productivity while decreasing EI (McAtee et al., 2025). Importantly, the impacts of animal health extend beyond individual animals, as health related effects accumulate at the cohort level and influence system wide sustainability outcomes.

Across disease categories, health challenges consistently reduce feed intake, growth rate, and feed efficiency while increasing days on feed and mortality. Although the biological mechanisms underlying these conditions differ, they ultimately have similar effects on production efficiency and environmental performance. Each pathway increases EI by extending maintenance requirements and resource use relative to productive output, thereby linking animal health directly to environmental performance in beef production systems.

The Role of Management and Technology in Emissions Mitigation

Health Management Interventions

Health management interventions represent a primary mechanism through which producers can influence both productivity and EI in beef production systems. Strategies to mitigate BRD for example are typically implemented at the cohort level, particularly at feedlot

arrival when cattle are most vulnerable to disease. These interventions commonly include metaphylaxis, treatment protocols, and preventative health management practices designed to reduce morbidity, mortality, and variability in animal performance. A wide range of pharmaceutical and biological products has been developed to manage BRD, with variable effectiveness reported across studies in terms of reducing disease incidence and improving health outcomes (Edwards, 2010; O'Connor et al., 2013; Stegner et al., 2013; Rogers et al., 2016; Abell et al., 2017; Hanratty et al., 2023). Beyond average treatment effects, health management strategies can influence the distribution of performance within cohorts by reducing variability in growth, feed efficiency, and survival. Reductions in performance variability have important implications for overall production efficiency, resource use, and sustainability outcomes within beef production systems.

Growth-Promoting and Efficiency Technologies

Growth-promoting and efficiency-enhancing technologies are commonly used in stocker and feedlot systems to improve animal performance and biological efficiency, thereby influencing EI through increased productivity rather than through offsets or post hoc mitigation. Technologies such as growth-promoting implants, ionophores, and beta-adrenergic agonists are widely implemented to increase ADG and improve G:F, contributing to improved feed efficiency and economic returns (Stackhouse et al., 2012). Despite these benefits, such technologies are often associated with consumer concerns and may be perceived as conflicting with certain societal definitions of sustainability. These technologies were developed and adopted primarily to improve productivity and economic efficiency rather than to achieve sustainability objectives, although they may reduce emissions intensity indirectly through improved efficiency.

Growth-promoting implants are routinely used in feedlot cattle to enhance feed efficiency and growth rate by increasing lean tissue accretion, which is closely associated with improved feedlot performance (Coopridge et al., 2007). Feedlot efficiency is strongly influenced by the rate of muscle accretion, as greater deposition of lean tissue increases productive output relative to maintenance requirements. Similarly, beta-adrenergic agonists function as metabolic modifiers by increasing lipolysis and protein synthesis while decreasing lipogenesis and protein degradation. These physiological shifts result in increased carcass leanness, ADG, and G:F (Mersmann, 1998; Strydom et al., 2009; Vogel et al., 2009).

Ionophores, particularly monensin sodium, improve nitrogen metabolism and feed efficiency in beef cattle primarily through alterations in ruminal fermentation, including increased propionate production (Bergen and Bates, 1984; Schelling, 1984). Additional mechanisms contributing to improved efficiency include increased G:F, stabilization of DMI, and inhibition of lactic acid producing bacteria in the rumen (Dennis et al., 1981; Duffield et al., 2012; Ellis et al., 2012; Wood et al., 2016). Through improved protein retention and energetic efficiency, ionophores reduce feed requirements per unit of gain while maintaining or enhancing animal performance, with associated reductions in EI (Tedeschi et al., 2003).

Collectively, feedlot management systems integrate combinations of metabolic modifiers, growth-promoting implants, ionophores, and other efficiency-enhancing practices to increase biological efficiency and reduce performance variability. Improvements in animal performance are achieved through coordinated advances in genetics, nutrition, management, and reproduction, with growth-promoting technologies representing one component of broader efficiency-driven production strategies (Boadi et al., 2004; Wileman et al., 2009). Importantly, these technologies influence emissions outcomes indirectly by increasing productivity and reducing the feed inputs

and time required to produce a unit of beef, reinforcing the role of biological efficiency as a central driver of EI in beef production systems.

Despite their demonstrated benefits for improving efficiency and reducing emissions intensity, some of these technologies, including antimicrobial use and growth-promoting compounds, may be perceived as conflicting with certain societal definitions of sustainability, highlighting the need to balance environmental, economic, and social dimensions within beef production systems.

Emerging Emissions-Specific Technologies

A range of technologies and management strategies aimed specifically at mitigating enteric CH₄ emissions from ruminant livestock are currently under development or evaluation (Arndt et al., 2022). These approaches include modifications to diet formulation (Broocks et al., 2016; Klopatek et al., 2022), genetic selection for lower CH₄ production (Fennessy et al., 2019; Goopy, 2019), and the use of targeted feed additives (Alemu et al., 2021; Vijn et al., 2020; Vyas et al., 2018).

Among feed additives, incorporation of the CH₄ inhibitor 3-nitrooxypropanol (3-NOP; DSM Nutritional Products, Kaiseraugst, Switzerland) has demonstrated consistent reductions in CH₄e production when included in both high-grain and high-forage diets (Romero-Perez et al., 2014; Vyas et al., 2016a,b). Feeding seaweed also has been shown to reduce CH₄ emissions, although reported responses remain highly variable across studies (Kinley et al., 2020). Ionophores such as monensin, which are widely used in commercial feedlot diets to improve energy and nitrogen utilization, have been associated with increased ruminal propionate production and improved G:F, with potential secondary benefits for CH₄ mitigation (Ruiz et al., 2001; Beauchemin et al., 2008; Appuhamy et al., 2013).

More recently, lubabegron (Exterior; Elanco, Greenfield, IN, USA) became the first U.S. Food and Drug Administration-approved feed additive for reducing gas emissions from an animal or its waste. Lubabegron has been shown to reduce estimated ammonia emissions (Kube et al., 2021; Wendler et al., 2025; Eekhoff et al., 2025) and CO₂e emissions in beef cattle systems (McAtee et al., 2024). Collectively, these emerging technologies illustrate the potential for emissions-specific interventions to complement efficiency-driven mitigation strategies, while underscoring the importance of evaluating their co-benefits, limitations, and interactions within commercial production systems. The effectiveness and adoption of emissions-specific technologies may depend on production phase, diet composition, cost, and potential interactions with animal performance and health, highlighting the need to evaluate both environmental benefits and system-level tradeoffs. Although these interventions differ in mechanism and motivation, they influence EI through a common pathway: changes in animal performance, health, and survival.

Despite increasing emphasis on sustainability in beef production, important gaps remain in how environmental outcomes are evaluated within commercial feedlot systems. Many sustainability assessments do not explicitly integrate animal health, performance variability, and mortality into emissions evaluation, instead relying on average-animal or system-level assumptions that obscure biologically meaningful sources of variation. In addition, relatively few studies jointly evaluate health interventions, production outcomes, and EI within a unified analytical framework using commercial-scale production data. These limitations constrain the ability of producers and industry stakeholders to determine whether management decisions that influence animal health and performance meaningfully align environmental outcomes with operational and economic realities.

Dissertation Outline

Together, the following chapters progress from evaluation of a targeted emissions reducing technology, to observational analysis of commercial feedlot data, to health intervention trials, culminating in a systems level synthesis of health, performance, and environmental outcomes. In Chapter 2, data from multiple U.S. commercial feedlots are used to examine associations between cattle health and production metrics, including growth rate, feed efficiency, disease burden, and mortality, and greenhouse gas emissions intensity (EI) across production conditions. In Chapter 3, the effects of the emissions-reducing feed additive lubabegron (Experior) are evaluated in a commercial feedlot setting, with comparisons to ractopamine hydrochloride (Optaflexx) to characterize differences in cattle performance, carcass characteristics, EI, and economic outcomes. In Chapter 4, outcomes from a randomized clinical trial are used to compare morbidity, mortality, and treatment success among macrolide antimicrobial options for first treatment of BRD in medium risk feedlot cattle. In Chapter 5, relationships among cattle health, performance, management interventions, and GHG EI are synthesized across production phases to evaluate the role of animal health as a driver of productivity and environmental outcomes in beef production systems. Finally, the key findings and conclusions of the dissertation are presented in Chapter 6.

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Chapter 2 - Pens of commercial feedlot cattle with better health and performance have lower estimated greenhouse gas emissions intensity

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Abstract

With increasing emphasis on sustainability, beef producers are evaluating potential environmental impacts of production practices. However, gaps remain in understanding how cattle health and performance metrics align with environmental impacts and global protein needs. This study quantified how feedlot performance and health metrics for beef-breed steers and heifers are associated with total greenhouse gas (GHG) emissions and emissions per unit of production. Using data on 9,436 single-lot pens in nine U.S. commercial feedlots (2017 to 2021), we fit mixed-effects multivariable models, based on directed acyclic graphs, to evaluate four key explanatory variables: average daily gain (ADG), feed efficiency (G:F), medicine costs per pen (proxy for disease burden), and cumulative mortality. Sex, season of arrival, days on feed, and arrival body weight were assessed as potential confounders. The primary outcome was estimated carbon dioxide equivalent emissions per kg of final body weight (emissions intensity), derived

from Uplook 1.0 (Elanco Animal Health). Across all study pens, 19.2% of estimated lifetime emissions occurred during the feedlot phase, while 41.8% of total body weight gain occurred at the feedlot; demonstrating how feedlots reduce emissions intensity and enhance production efficiency. Higher ADG and G:F were associated with lower emissions intensity, while higher mortality and disease burden were linked to increased emissions intensity. Significant interactions were observed in all models, with effects of ADG and G:F modified by sex and season (P values < 0.01). Improved growth and feed efficiency were consistently associated with lower emissions, but the magnitude of effects differed between steers and heifers and varied by season. Disease burden and mortality impacts also varied by season and arrival weight, with significant three-way interactions (P values < 0.01). Pens with poorer health consistently had higher emissions intensity, with the largest effects in lighter-weight pens during certain seasons. This study quantifies how improving health, G:F, and ADG can reduce emissions intensity. For example, reducing mortality from 5% to 0% lowers lifetime emissions by nearly 6%. Findings highlight the importance of health and performance in sustainability and help quantify potential impacts of strategies for improving health and performance to reduce GHG emissions intensity and improve production efficiency.

Key words: beef cattle, efficiency, emissions intensity, sustainability

Lay Summary

Current gaps exist in defining how commercial feedlot cattle health and production metrics align with environmental impacts and global protein needs. This study analyzed data from over 9,400 feedlot pens across nine U.S. commercial feedlots to assess how growth rate, feed efficiency, disease burden, and mortality affect estimated greenhouse gas emissions. Results showed that cattle with higher growth rates and better feed efficiency had lower estimated

emissions intensity, whereas increased mortality and disease burden were linked to higher emissions. For example, reducing mortality from 5% to 0% was estimated to lower lifetime emissions by nearly 6%. However, the effects of disease burden and mortality on estimated emissions varied significantly among seasons of the year and by the average weight of cattle at feedlot arrival, with the greatest effects in lighter-weight cattle during specific seasons. Similarly, the effects of growth rate and feed efficiency on emissions varied significantly between heifers and steers, as well as by season. These study findings demonstrate how cattle health, feed efficiency, and growth rate are associated with estimated greenhouse gas emissions per unit of beef produced. By understanding these relationships, producers and industry stakeholders can implement targeted strategies to enhance both sustainability and protein production.

Introduction

Sustainability has emerged as a prominent theme within the beef cattle industry, though interpretations and implications can vary based on marketing intentions and user perspectives (Zepeda et al., 2013). At its core, sustainability encompasses three key components: environmental responsibility, economic viability, and social acceptability (de Wit et al., 1995; United Nations, 2005). However, in the beef industry the term sustainability is often interpreted with a focus on greenhouse gas (GHG) emissions. Notably, diverse stakeholders within the beef industry sector have proposed sustainability goals, largely centered around mitigating GHG emissions (U.S. Roundtable for Sustainable Beef, 2022). The complexities of GHG emissions in beef cattle production arise from the diversity of their sources and the interactions among them, including methane (CH₄) generated through enteric fermentation and manure decomposition, carbon dioxide (CO₂) resulting from land-use changes and the use of fossil fuels, and nitrous

oxide (N_2O) emitted from nitrogenous fertilizers, manure application, and pen surfaces (EPA, 2023). Yet, the challenge of decreasing ruminant production GHG emissions is difficult given the projected increase in demand for ruminant milk and meat in the upcoming decades and the limited current options of available reduction strategies (Beauchemin et al., 2020).

Grazed and grain-fed cattle exhibit different patterns of GHG emissions, with grazing leading to heightened emissions (Capper, 2012). Cattle eating more roughage have more hydrogen available for methanogenesis, and therefore produce more enteric CH_4 (Ungerfeld, 2020). Further, starch lowers the pH in the rumen and hydrogen available for methanogenesis, thus limiting CH_4 production in higher starch diets such as those fed in feedlots (Van Kessel and Russell, 1996). The cow-calf phase of beef production, characterized by a diet high in roughage, is responsible for the majority of life-time emissions compared to the feedlot phase, where a grain-based diet predominates (Rotz et al., 2015).

Life cycle assessments (LCAs) have been used to evaluate the potential environmental impact of beef production systems (Pelletier et al., 2010; Capper, 2011; Stackhouse et al., 2012). The LCAs are standardized approaches to quantify environmental impacts of a system from birth to departure of the system, and are comprised of a system boundary, an inventory of all relevant data, and analysis of inputs (ISO, 2006). Many LCAs of beef productions systems show varying results due to differences in methods and data sources (Werth et al., 2021). System boundaries in LCAs can vary significantly, ranging from the inclusion of only direct emissions, such as CH_4 from enteric fermentation, to more comprehensive scopes that also account for indirect emissions, like those from feed production or manure management. Similarly, management practices such as diet formulation, housing systems, and manure handling differ across operations, leading to variations in estimated emissions and environmental impacts (Lupo et al.,

2013). A LCA specifically focused on feedlots, which concentrates on cattle housed in confinement and fed a high-energy diet, would yield more precise insights into GHG emissions and resource use efficiency by separating the effects of feedlot-specific practices, such as ration composition, manure management, and feed conversion efficiency. This contrasts with broader LCAs that often include extensive grazing systems, which can obscure the details of feedlot operations (Lupo et al., 2014).

Using fewer resources to produce more beef inherently leads to an increase in production efficiency and enhanced sustainability. The amount of beef produced in 2007 required 67% of land, 87.9% of water, 81.4% of feed, and only 69.9% of animals compared to equivalent beef systems in 1977 (Capper, 2011). Feedlots in 2022 produced the same amount of beef as feedlots in 1999, with 13% fewer animals (Betts and Harborth, 2024). Increased animal productivity, requiring fewer inputs—such as feed, water, and energy—to produce the same product, is more sustainable (Stackhouse et al., 2013; Broocks et al., 2016). Animal health also has a major impact on sustainability, as greater than 20% of animal protein is lost to disease globally (OIE, 2015). However, current gaps exist in defining how commercial cattle health and production metrics align with environmental impacts and global protein needs. Emissions intensity is defined as the amount of GHG emissions (kg CO₂e) produced per kilogram of final body weight (FBW) or beef produced. Therefore, our objectives were to quantify how health and performance metrics in beef-breed feedlot steers and heifers are associated with estimated GHG emissions and emissions intensity. Secondary objectives were to demonstrate differences in estimated emissions across production phases and compare emissions when described on a per-animal basis versus a per unit of beef production (intensity) basis. Our hypothesis was that standard pen-level feedlot operational data on average daily body weight gain (ADG), feed efficiency as a

ratio of body weight gain to weight of feed (G:F), total medicine costs per initial number of animals in the pen (n) as a proxy for disease burden, and cumulative all-cause mortality could be used as practical indicators of estimated emissions intensity, which in turn may help producers operationalize sustainability goals.

Materials and Methods

Data

In 2023, we collected retrospective cumulative pen-level (close-out) data that were recorded in 13 High Plains U.S. (Kansas and Nebraska) feedlots on 13,689 pens of cattle that arrived to the feedlots during 2017 to 2021. Pens were defined as single pen lots, groups of purchased cattle housed within a single pen during the feedlot phase. In commercial feedlot production systems, these pens (lots) are the common aggregate unit. Pen-level variables regularly collected across these feedlots included sex, arrival date, mean body weight on arrival at the feedlot, days on feed (DOF; calculated as the total number of head-days cattle were fed divided by the number of cattle shipped from the pen), total medicine costs, cumulative mortality (defined as the proportion of cattle that died during the feeding period), and estimated GHG emissions. Study inclusion criteria included: pens classified as single pen lot, beef cattle, steer or heifer (not mixed), that arrived at the feedlots between 2017 and 2021, mean arrival body weight greater than 227 kg and less than 454 kg, and from a feedlot with more than 100 pens included in the dataset. After refining the study population, there were a total of 9,436 pens from 9 different feedlots. All pens in the dataset were assumed to have received monensin. Implant data were available for 98% of pens (Table 1; 9,245 of 9,436). Beta-agonist use was inconsistently recorded, with 93% of pens (8,780 of 9,436) missing these data. In these cases, nonuse was

assumed resulting in conservative emissions estimates and applied consistently across all feedlots' data.

To address linearity assumptions, several continuous variables were categorized for analysis including, ADG, G:F, DOF, total medicine costs, and arrival body weight variables. The categorization process was based on natural breaks, practical industry standards, or biological considerations in the distribution of the variables (Dohoo et al., 2009). Additionally, this approach resulted in relatively equal sample sizes within categories (Table 1). Total medicine costs included the pens' cumulative costs for all pharmaceutical interventions given to animals in the pen, including therapeutic antimicrobials, metaphylaxis, vaccinations, labor, and other health-related treatments. Costs were standardized per animal placed to enable pen-level comparisons. The variable for total medicine costs per initial number of animals in the pen (n), used as a proxy for disease burden, was categorized into the following five groups: <16.00, 16.00 to 19.99, 20.00 to 29.99, 30.00 to 54.99, and ≥ 55.00 dollars per animal placed. Average daily 272 kg, 273 to 318 kg, 319 to 363 kg, 364 to 409 kg, and 410 to 454 kg. Days on feed were aggregated into 20-d increments to account for non-linearity in the data and provide a balanced and effective grouping for analysis. This resulted in the following 13 categories: 60 to 79, 80 to 99, 100 to 119, 120 to 139, 140 to 149, 160 to 179, 180 to 199, 200 to 219, 220 to 239, 240 to 259, 260 to 279, 280 to 289, and 300 to 319 d. In addition, cumulative mortality was categorized into five categories based on the percentage of the initial animal count that died from any cause during the feeding period: 0, 0.1 to 1.9, 2 to 4, 5 to 10, and $\geq 11\%$.

Production emissions data were derived from a proprietary LCA inventory accounting system, Uplook 1.0 (Elanco Animal Health), that estimated emissions based on carbon dioxide equivalents (CO_2e ; Horton et al., 2023; McAtee et al., 2024). Methodologies from the U.S.

Department of Agriculture (USDA; USDA, 2014), the Intergovernmental Panel on Climate Change (IPCC, 2023), and the US Environmental Protection Agency (EPA; EPA, 2024) were incorporated into GHG emission calculations. Feedlot system inputs included total feed intake, diet formulation, feedlot energy use, the number of initial animals, total initial body weight, breed, animal-days, animal removals and mortalities, the number of harvested animals, FBW, and hot carcass weight (HCW). The system converted all GHG emissions to CO₂e for analysis, using the conversion factors outlined in the IPCC Sixth Assessment (IPCC, 2023). Pre-feedlot calf estimates, representing the carbon footprint of animals received, were based on a process model of the cattle cycle representing the emissions to support cows, bulls, and replacement heifers and growing calves from birth to initial feedlot weight. These estimates accounted for CH₄ emissions, manure management, pasture fertilization, supplemental feeding, as well as fuel and electricity usage on the farm, including the transportation of cattle to the feedlot. The system incorporated the effects of feed production, considering emissions of CO₂, N₂O, and CH₄ stemming from the cultivation, planting, fertilizing, pesticide application, harvesting of individual ingredients and transport; these estimates were based on established carbon footprint data for feed ingredients from published sources (Adom et al., 2012, 2013). Additionally, feedlot emissions accounted for enteric CH₄, manure CH₄, manure N₂O, and CO₂ emissions from energy use. Total assessed emissions align to the cradle to gate approach described by the Global Roundtable for Sustainable Beef (GRSB) carbon footprint guideline (GRSB, 2022). Enteric CH₄ factors were modified based on USDA guidelines (USDA, 2014). The final values of CO₂e were estimated per animal in the pen, and per unit of beef production, specifically live body weight and HCW (Horton et al, 2023; McAtee et al., 2024). The dataset did not consistently include a

corresponding HCW for each pen, therefore CO₂e values per unit of FBW were used to represent emissions per unit of beef production (i.e., emissions intensity).

Information sourced from Uplook 1.0, a deterministic model, undergoes an auditing procedure, wherein data from affiliated account and animal health software systems are received by a central server. These data are then populated into real-time tables, comprising both raw data and computed fields. Subsequently, a data engine assesses whether the calculated values deviate from the 5th and 95th percentiles of the preceding rolling 12 mo. Any discrepancies prompt manual verification or correction of the data. Upon completion of data reconciliation, results are published into final data tables (Betts and Harborth, 2024). Feedlot performance data were combined on a pen basis with the corresponding emissions estimates by the unique identifier for each pen within each feedlot and year. The resulting dataset included variables of feedlot performance with the outcome variables of emissions estimates.

Calculations for Descriptive Statistics

Mean values for GHG emissions were calculated across all pens to describe emissions contributions at different production phases. Figure 1 presents the mean total lifetime kg CO₂e per pen, partitioned into emissions from the cow-calf phase and the feedlot phase, stratified by steer and heifer pens. These values were calculated by averaging the total lifetime kg CO₂e for each phase across all pens within each sex category.

Figure 2 presents emissions intensity estimates at two production stages. The incoming calf emissions intensity was calculated as the mean total kg CO₂e per kg arrival body weight, averaged across all pens. The prior to harvest emissions intensity was calculated as the mean total kg CO₂e per kg FBW, also averaged across all pens.

Directed Acyclic Graphs

Directed acyclic graphs (DAG) were used to illustrate causal diagrams and guide the model building process for these observational data analyses (Greenland et al., 1999). On the basis of four causal diagrams defined a priori (Figure 3), ADG, G:F, total medicine costs, and cumulative mortality were each considered the main factors of interest in four separate models. Variables pertaining to sex (steers and heifers), season (winter, January through March; spring, April through June; summer, July through September; and fall, October through December), DOF categories, and arrival body weight categories were considered a priori as potential confounders of the relationship between each of the main factors of interest and the emissions outcome.

Multivariable Statistical Models

Pair-wise correlation analyses were performed using the Spearman rank correlation statistic to identify possible collinearity among the variables of ADG, G:F, mortality, total medicine costs, arrival weight class, and DOF. If the value of the correlation statistic was $|0.8|$ or higher, only one of the variables would have been selected to be included into the multivariable model (Dohoo et al., 2009). The pairwise correlation coefficients among variables are presented in Table 2.

Associations between feedlot pen-level performance indicators and estimated GHG emissions were assessed using linear mixed models (Proc GLIMMIX) built in SAS 9.4 (SAS Institute Inc., Cary, NC, USA), with a Gaussian distribution, identity link function, and maximum likelihood estimation based on Newton-Raphson approximation with Ridging optimization technique. The primary outcome of interest was the lifetime kg of CO₂e estimated emissions intensity (lifetime kg CO₂e/kg FBW). A cross-classification of feedlot-years was

included as a random intercept to model the overdispersion arising from the lack of independence of pens nested within feedlots and arrival years.

The main effects model was initially constructed by including the main factors of interest (ADG, G:F, total medicine costs, cumulative mortality) and confounders established a priori (sex, season of arrival, arrival weight class, and DOF). Bivariable analyses assessing the associations between each of the main factors of interest and one confounder at a time were tested for significance ($P < 0.05$). Two-way interactions were tested by incorporating the interactions one at a time into the multivariable main effects models. If these interactions were significant ($P < 0.05$), they were kept in the models. A three-way interaction (and its corresponding two-way interactions) among arrival weight, season of feedlot arrival, and ADG, G:F, total medicine costs, or mortality also were tested in all four models. Normal quantile plots of best linear unbiased predictors for the random variables in the models (feedlot and year of arrival) and residual plots of individual-level residuals were visually examined to assess model fit. Model-adjusted means, their 95% confidence intervals, and P values were estimated and reported.

Results

Descriptive Statistics

A total of 9,436 pens (representing 1,103,761 cattle arriving to the feedlots) from 9 different feedlots during arrival years 2017 to 2021 were included in the final dataset. The mean number of cattle within pens was 119 (SE = 0.57) with a median of 112 animals. Fifty-six percent of the pens were classified as heifers and 44% as steers. Pen mean cattle arrival body weight ranged from 227 to 453 kg, with a median of 349 kg and a mean of 348 kg (SE = 0.47 kg). Average daily weight gain ranged from 0.63 to 2.40 kg/day, with a median of 1.54 kg/day

and a mean of 1.55 kg/day (SE = 0.002 kg/day). Gain to feed ranged from 0.06 to 0.24, with a median and mean of 0.16 (SE = 0.0002). Average medicine costs ranged from \$0.21 to \$127.09, with a median of \$18.88 per animal placed and a mean of \$22.73 (SE = 0.12). Mortality ranged from 0% to 29.85%, with a median of 1.31% and a mean of 1.73% (SE = 0.02%). Further details are presented in Table 1. Emissions estimates ranged from 11.32 to 20.50 kg CO₂e/kg FBW, with a median of 13.52 kg CO₂e/kg FBW and a mean of 13.53 kg CO₂e/kg FBW (SE = 0.80 kg CO₂e/kg FBW).

Averaged across all pens of steers and heifers, 80.83% of the total lifetime emissions estimates occurred during the pre-feedlot (cow-calf) phase (Figure 1). The total emissions estimates during the feedlot phase for steers and heifers were 20.0% and 18.5% respectively. While the feedlot phase contributed a smaller percentage of total emissions, it is a critical stage for efficiency gains, as 41.8% of total weight gain occurred during the feedlot phase in this dataset. Furthermore, emissions intensity is reduced by 27% from the incoming calf stage (kg CO₂e/kg of incoming weight) compared to harvest stage (kg CO₂e/kg of FBW), demonstrating the significant efficiency improvements achieved during the feedlot phase (Figure 2). Estimated emissions can be described on a total per animal or per unit of production basis, either for the entire lifetime or only during the finishing phase. Conclusions depend on how the results are described. For example, contrasting patterns emerge when emissions estimates are described on a total per animal in a pen basis versus a per unit of production basis. As cumulative mortality increases, the total finishing emissions estimates per animal in the pen decreases, whereas total lifetime estimated emissions per kg of beef production (FBW) increases (Figure 4). Since an increase in mortality is not a desirable outcome for beef production systems, for the remainder of this paper, emissions estimates are described as lifetime emissions intensity (kg CO₂e/kg FBW).

Multivariable Analyses

Association of ADG with emissions intensity.

The final multivariable model of ADG on estimated lifetime emissions intensity included main effects of ADG ($P < 0.001$), sex of the pen ($P < 0.001$), and season of feedlot arrival ($P < 0.001$). Potential confounders included were cumulative mortality ($P < 0.001$), arrival body weight ($P < 0.001$), and DOF ($P < 0.001$). Significant interactions were observed between ADG and sex ($P < 0.001$) and ADG and season ($P < 0.001$), while the three-way interaction between ADG, sex, and season of arrival was not significant ($P = 0.053$). Results from this model are reported in Supplementary Table 1. Model-estimated means of estimated lifetime kg CO₂e/ kg FBW for ADG were assessed for each sex (Figure 5) and season (Figure 6).

Overall, pens with lower ADG had higher estimated lifetime emissions intensity. However, due to the significant interactions between ADG and sex, as well as ADG and season, the effect of ADG must be interpreted in the context of these interactions. For instance, in the ADG by sex interaction (Figure 5), heifers consistently exhibited higher estimated emissions intensity than steers across all ADG categories, with the magnitude of this difference varying by ADG category. This indicates that the relationship between ADG and emissions intensity is not uniform and is influenced by both sex and seasonal factors.

Similarly, the significant interaction between ADG and season (Figure 6) indicated that for all seasons, as ADG increased, estimated emissions intensity decreased. While the overall pattern appeared consistent across seasons, contrasts within the interaction revealed that the magnitude of the relationship between ADG and emissions

intensity differed significantly between seasons, further highlighting the impact of season-specific factors on emissions outcomes.

Association of G:F with lifetime emissions intensity.

The final multivariable model of G:F on estimated lifetime emission intensity included main effects of G:F ($P < 0.001$), sex ($P < 0.001$), and season of arrival ($P < 0.001$). Potential confounders included were cumulative mortality ($P < 0.001$), arrival body weight ($P < 0.001$), and DOF ($P < 0.001$). Significant interactions were observed between G:F and sex of the pen ($P < 0.001$) and G:F and season of feedlot arrival ($P < 0.001$), while the three-way interaction between G:F, sex, and season of arrival was not significant ($P = 0.671$). Results from this model are reported in Supplementary Table 2. Model-estimated means of estimated lifetime emissions intensity for G:F were assessed for each sex (Figure 7) and season (Figure 8).

The significant interaction term between G:F and sex (Figure 7), indicated that heifers exhibited higher estimated emissions intensity than steers across most G:F categories, except for the first category (<0.100) where the difference was not significant ($P = 0.560$). The significant interaction between G:F and season (Figure 8) revealed that as G:F increased, the estimated lifetime emissions intensity consistently decreased during spring, summer, and fall, demonstrating a clear trend of improved efficiency with higher G:F. In contrast, winter exhibited a less pronounced decline in emissions intensity as G:F increased, suggesting that the relationship between G:F and emissions intensity in winter may be influenced by additional factors or variability not observed in the other seasons.

Association between disease burden (medicine cost) with lifetime emissions intensity.

The final multivariable model of disease burden on estimated lifetime emissions intensity included main effects of disease burden ($P < 0.001$), season of feedlot arrival ($P = 0.020$), and arrival body weight ($P < 0.001$). Sex of the pen ($P < 0.001$) was included as a potential confounder. Significant interactions were observed between disease burden and arrival body weight ($P < 0.001$), while the three-way interaction between disease burden, season of feedlot arrival, and arrival body weight was also significant ($P < 0.001$). Results from this model are reported in Supplementary Table 3. Model-estimated means of estimated emissions intensity for disease burden were computed and displayed for the arrival weight groups by each season (Figure 9).

When considering the significant interaction among season, disease burden, and arrival body weight, pens with higher disease burden incurred higher estimated lifetime emissions intensity in certain seasons and arrival body weight classes. Across all seasons, medicine costs in lighter arrival weight categories were associated with greater increases in emissions intensity compared to heavier weight categories (Figure 9). For example, in Spring, pens with total medicine costs below \$16.00 had the lowest emissions intensity, with emissions intensity increasing progressively in pens with higher medicine costs, peaking in the $\geq \$55.00$ category. Similar patterns were observed in Summer, Fall, and Winter, where higher medicine costs consistently corresponded to greater emissions intensity (Figure 9). Heavier arrival body weight categories (e.g., 410 to 454 kg) generally exhibited lower emissions across all medicine cost categories and seasons (Figure 9). For instance, summer-arriving pens in the 227 to 272 kg weight category with $\geq \$55.00$ in medicine costs had the highest emission intensity, while pens in the 410 to 454 kg category with \$16.00 to \$19.99 in medicine costs had the lowest emissions

intensity estimates within the season (Figure 9). Heavier body weight categories consistently demonstrated lower emissions intensity compared to lighter pens within the same medicine cost category and season.

Association of mortality with lifetime emissions intensity.

The final multivariable model of mortality on estimated lifetime emissions intensity included the main effects of cumulative mortality ($P < 0.001$), season of feedlot arrival ($P < 0.001$), and arrival body weight ($P < 0.001$). Sex ($P < 0.001$) was included as a potential confounder. Significant interactions were observed between mortality and season of feedlot arrival ($P < 0.001$) and mortality and arrival body weight ($P < 0.001$), while the three-way interaction between mortality, season of feedlot arrival, and arrival body weight was also significant ($P = 0.003$). Results from this model are reported in Supplementary Table 4. Model-estimated means of estimate lifetime emissions intensity for mortality were calculated and displayed for the arrival body weight groups by each season (Figure 10).

When considering the three-way interaction among season, mortality categories, and weight categories on lifetime emissions intensity, pens with higher cumulative mortality had higher emissions intensity in certain seasons and weight classes (Figure 10). In all seasons, lighter arrival weights generally corresponded to higher emissions intensity compared to heavier categories within mortality categories (Figure 10). Specifically, in Spring, emissions intensities were lowest in all weight classes for the 0% mortality category, rising with increasing mortality and peaking with 11+% mortality category. This trend was similarly observed in Summer, Fall, and Winter, where 0% mortality recorded the lowest emissions intensity, and 11+% mortality recorded the

highest (Figure 10). Notably, heavier weight categories (410 to 454 kg) consistently showed lower emissions intensity across all seasons and mortality categories. For example, 273 to 328 kg pens arriving in the Spring with cumulative mortality >11% had the highest lifetime emissions intensity estimates, while summer-arriving 410 to 454 kg pens with no mortality had the lowest estimated lifetime emissions intensity (Figure 10), resulting in a relative difference of 26.87%. Overall, higher cumulative mortality contributes to increased lifetime emissions intensity in beef production, but heavier weight categories consistently exhibit lower emissions intensity within each mortality category and season.

Discussion

This study addressed crucial gaps in understanding and quantifying the relationships between estimates of emissions intensity and commonly utilized feedlot metrics of cattle health and production. It has become imperative to elucidate how key cattle production drivers of GHG emissions, such as ADG, G:F, disease burden, and mortality influence emissions intensity estimates in beef-breed steers and heifers in commercial feedlots, particularly in the context of sustainability within the beef industry. Understanding these relationships enables stakeholders to identify areas for targeted interventions to reduce relative emissions intensity. Moreover, incorporating causal thinking into data analyses ensures that observed associations reflect true underlying effects rather than spurious or biased conclusions (Weistrech and Greenland, 2012; Bandoli et al., 2018).

To identify and quantify these relationships accurately, DAGs were used to guide the analysis and prevent biased interpretation (e.g., “table 2 fallacy”) of observed associations (Weistrech and Greenland, 2012; Bandoli et al., 2018). The DAG frameworks incorporated

confounders such as sex, arrival weight, and season to distinguish direct effects from indirect effects. For instance, the relationship between ADG and estimated lifetime emissions intensity is influenced by confounders like sex and season, which affect both ADG and emissions intensity. Neglecting these confounders could have led to misinterpretation of the causal pathways and inappropriate conclusions about potential impacts of interventions.

Most emissions during a beef animal's lifetime occurred during the cow-calf phase, estimated here at approximately 80% for both steers and heifers, which is consistent with previous research (Beauchemin et al., 2010). While the feedlot phase only contributes approximately 20% of lifetime emissions, 41.8% of total lifetime body weight gain occurred at the feedlot, highlighting the feedlot's importance in enhancing production efficiency and reducing emissions intensity.

Heifers, comprising 56% of feedlot pens in our dataset, exhibited higher estimated emissions per kg FBW compared to steers, which is consistent with sex-related differences in growth and efficiency. Steers grow faster, are more efficient, and finish at heavier weights compared to heifers (Zinn et al., 2008), contributing to their lower emissions intensity. Variations in emissions intensity also may be influenced by seasonal patterns and genetic factors. For instance, cattle with greater Brahman influence, commonly raised in the southern U.S. due to their adaptability to heat and humidity (Hansen, 2004), are often placed in feedlots at strategic times of the year to maintain consistent placement flows (Peel, 2003), and these cattle types may differ in terms of performance and emissions intensity. In this study region, production cycles are shaped by environmental factors such as climate and forage availability, which affect the timing of key management stages, including weaning, backgrounding, and feedlot entry (Peel, 2003). Differences in emissions intensity are influenced not only by feedlot practices but also by

upstream factors, such as genetic and environmental influences, which were not directly included in the causal models analyzed in this study.

Improved ADG and G:F were consistently associated with lower emissions intensity, reflecting improved resource efficiency. Feedlot cattle gaining weight more efficiently require less feed per unit of weight gain, which reduces enteric CH₄ emissions. This aligns with previous findings demonstrating that an increase in ADG is associated with reduced enteric CH₄ emissions (Min et al., 2022) . However, the effects of sex and season were found to modify this relationship, highlighting its complexity. For example, higher ADG consistently reduced emissions intensity, but the magnitude of reduction varied depending on sex and season. Similarly, improved G:F reduces emissions intensity as previously demonstrated (Coopridge et al., 2011), but again the magnitude of this association was modified by both sex and season. Thus, while improved ADG and G:F were both strongly associated with reduced emissions intensity, the estimated effects need to be considered in context of season and sex. This growing evidence of animal performance impacts on emissions intensity underscores the importance of growth efficiency-focused strategies in feedlot production systems.

Season of feedlot arrival significantly modified the relationships between live cattle performance metrics and emissions intensity. One potential explanation for this interaction is seasonal variation in maintenance energy requirements (Declurto-Wyffels et al., 2021). Additionally, seasonal differences in growth rates directly affect overall weight gain and G:F (Babcock et al., 2010), both of which play a key role in shaping emissions intensity outcomes. These insights can guide producers in optimizing strategies, such as feedlot arrival timing or feed regimens, to minimize emissions intensity while maintaining productivity.

Minimizing disease burden and reducing mortality improves overall herd health and productivity, and decreased emissions intensity per unit of beef produced. Our results demonstrated that higher medicine costs (used as a proxy for disease burden), particularly in lighter pens, were consistently associated with increased emissions intensity, primarily due to lower FBW. Lighter arrival weights are associated with higher disease risks (Babcock et al., 2012), which can compromise growth performance, decrease FBW, and thus increase overall emissions intensity. For example, summer pens with the lightest arrival weights and highest medicine costs exhibited the highest emissions intensity. Causal models allowed us to attribute these increases in emissions intensity to both the direct effects and the indirect effects of disease burden.

Cumulative mortality also significantly influenced emissions intensity. For example, an increase in cumulative mortality from 0% to 5% was associated with a 5.93% increase in emissions intensity across all lots in the analysis. This reflects the inefficiencies of resource losses—feed, water, and land—that are invested in animals that fail to reach market weight. Similar to disease burden, summer-arriving pens with lighter weight categories (227 to 363 kg) and the highest mortality also exhibited the greatest emissions intensity.

Overall, these findings highlight how lighter arrival weights, higher cumulative mortality, and seasonal conditions interact to influence emissions intensity, emphasizing the need for targeted disease management to mitigate potential environmental impacts. Our results provide empirical, quantitative evidence of the pen-level impact of health and performance on sustainability, which has not previously been documented. By integrating causal thinking, such as DAG-guided adjustments, into analyses we ensure these conclusions are robust and the potential impacts of actionable interventions can be accurately estimated. Incorporating animal

health and performance data into sustainability assessments and intervention strategies is critical for achieving meaningful reductions in beef production's carbon footprint. Suboptimal health and performance outcomes not only affect economic sustainability, but also contribute to higher per-unit emissions intensity (Capper and Bauman, 2013; Capper and Williams, 2023).

While this study focused on beef cattle, the rising number of dairy-beef crosses in feedlots presents an important area for future research (Foraker et al., 2022; Fuerniss et al., 2023; Jaborek et al., 2023). Distinct rearing practices between dairy-beef crosses and conventional beef breeds create substantial variations in their emission footprints (Rotz et al., 2019). In future studies, causal models will be essential in disentangling the direct effects of feedlot management practices from influences of cattle type.

When evaluating emissions across production phases or estimating intervention impacts, expressing emissions per unit of production (e.g., FBW or HCW) rather than total lifetime values provides more actionable insights for producers. For example, higher feedlot mortality reduces total emissions simply because fewer animals remain alive, but this overlooks the wasted resources invested in those animals and the goal of sustainable protein production. Our analysis reveals that high mortality indirectly inflates pen-level estimates of emissions intensity by reducing the denominator (FBW).

While this study provides valuable insights, some key limitations should be noted. First, HCW rather than FBW would be preferable to better represent total beef yield, but HCW data were unavailable for all pens, necessitating the use of FBW for consistency. Second, our disease burden (morbidity) estimates relied on veterinary medicine costs as a proxy, but more specific morbidity data from each feedlot would enhance accuracy. Third, initial calf emission estimates were based on breed and starting body weight, assuming that all other pre-feedlot production

factors (e.g., genetics, climate, and cow-calf management practices) remained constant. While this enabled standardization for comparing feedlot performance, this process model will not capture the full variability in cow-calf phase emissions associated with diverse production systems.

Conclusion

Although the feedlot phase only accounts for approximately 20% of total lifetime estimated emissions intensity, it remains crucial to thoroughly understand the influence of productivity and efficiency factors for mitigating GHG emissions intensity within beef production. This study quantifies how productivity and efficiency metrics, such as ADG and G:F, are associated with estimated emissions intensity, underscoring the importance of optimizing animal performance to reduce potential environmental impacts of beef production. Sex of the pen, season of feedlot arrival, DOF, and arrival weight were considered as potential confounders of the main explanatory factors (ADG, G:F, mortality, and health burden) to ensure the estimated effects are interpreted correctly within the broader context of factors influencing emissions. Reducing disease burden and mortality are critical to ensure more resources are efficiently converted into marketable meat, decreasing emissions per unit of beef produced. Sex of the pen also influences emissions intensity, with heifers exhibiting higher estimated emissions per kg FBW than steers. Seasonal variations further modify associations with emissions, reinforcing the importance of documenting the influence of health and performance metrics in the context of the production environment. These findings provide valuable insights, quantifying how health and productivity factors are associated with GHG emissions intensity, and offering data-driven estimates to inform measurable goals for more sustainable beef production.

Supplementary Data

Supplementary data are available at *Translational Animal Science* online.

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Author Contributions

Taylor McAtee (Formal analysis, Investigation, Writing - original draft), David Renter (Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing - review & editing), Nick Betts (Data curation, Investigation, Software, Writing - review & editing), and Natalia Cernicchiaro (Formal analysis, Methodology, Writing - review & editing).

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Conflict of Interest Statement

No authors have competing interests to declare.

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Tables and Figures

Table 2.1. Descriptive characteristics of the retrospective cumulative pen-level (close-out) data from 9,436 pens representing 1,103,761 cattle arriving to 9 different feedlots during arrival years 2017 to 2021.

Item	Feedlot									Avg.
	A	B	C	D	E	F	G	H	I	
Number of pens	1609	518	2625	735	340	553	366	2561	129	1048
Pens fed SFC versus HMC*, %	78	81	100	100	83	67	100	100	0	79
Pens received implant, %	98	98	99	95	95	95	97	100	89	96
Steer pens, %	46	41	48	38	27	40	54	40	65	44
Heifer pens, %	54	59	52	62	73	60	46	60	35	56
Arrival Weight Class, n										
227-272	41	49	149	23	20	59	46	163	2	61
273-318	228	142	448	163	83	160	87	508	18	204
319-363	601	166	932	260	130	190	128	950	52	379
364-409	526	132	784	219	89	109	69	714	42	298
410-454	213	29	312	70	18	35	36	226	15	106
Season of Arrival, n										
Winter	435	101	633	196	79	97	88	605	32	252
Spring	318	104	723	179	70	144	60	693	35	258
Summer	443	131	624	199	95	150	136	669	28	275
Fall	413	182	645	161	96	162	82	594	34	263
DOF*										
Average	153.5	170.0	157	160.0	169.9	170	170.0	155.6	160.3	158.7
Range	85-262	88-282	96-271	105-237	104-264	78-253	105-302	82-275	123-236	-
Median	151	165	154	158	164	168	165	152	157	155
ADG*, kg/day										
Average	1.56	1.45	1.55	1.52	1.39	1.51	1.51	1.62	1.52	1.51
Range	0.63-2.35	0.88-2.27	0.79-2.32	0.78-2.15	0.81-1.93	0.80-2.19	0.94-2.24	0.75-2.40	0.75-1.95	-
Median	1.54	1.44	1.54	1.51	1.37	1.49	1.51	1.61	1.54	1.51
G:F*										
Average	0.153	0.148	0.162	0.156	0.146	0.159	0.165	0.164	0.135	0.159
Range	0.055-0.198	0.093-0.240	0.099-0.207	0.102-0.188	0.100-0.197	0.101-0.199	0.118-0.210	0.084-0.207	0.073-0.164	-
Median	0.154	0.148	0.162	0.157	0.147	0.159	0.165	0.164	0.135	0.159
Medicine Costs, \$/animal										
Average	22.90	25.60	23.50	30.00	30.65	27.31	27.37	16.54	21.33	22.90
Range	11.33-91.4	4.31-113.16	3.08-111.16	5.30-127.09	7.30-112.89	0.73-108.5	5.52-94.93	4.58-80.3	0.21-98.02	-
Median	18.79	19.815	20.51	24.59	22.205	22.15	22.56	15.71	13.88	18.79
Cumulative Mortality, %										

Average	1.84	2.59	1.69	1.88	2.15	2.44	1.81	1.21	2.72	1.73
Range	0.00-29.21	0.00-16.18	0.00-14.00	0.00-22.50	0.00-23.73	0.00-24.18	0.00-13.24	0.00-19.15	0.00-29.85	-
Median	1.39	1.93	1.33	1.43	1.57	1.61	1.49	0.94	1.48	1.31

*SFC = Steam flaked corn; HMC = High moisture corn; DOF = Days on feed; ADG = Average daily gain; G:F = Gain-to-feed ratio

Table 2.2. Pairwise Spearman rank correlation coefficients among production, health, and management variables: ADG category, G:F category, cumulative mortality category, arrival weight class, DOF category, and categorized total veterinary medicine costs per animal.[†]

Variable 1	Variable 2	Correlation Coefficient
Arrival weight class	ADG	0.24
Arrival weight class	G:F	-0.11
Arrival weight class	Mortality	-0.29
Arrival weight class	DOF	-0.7
GF	ADG	0.41
Mortality	ADG	-0.27
DOF	ADG	-0.21
Mortality	G:F	-0.25
DOF	G:F	0.06
Mortality	DOF	0.33
Arrival weight class (kg)	Total medicine costs/animal	-0.29
Total medicine costs/animal	DOF	0.33
Total medicine costs/animal	ADG	-0.21
Total medicine costs/animal	G:F	-0.08

[†]ADG = average daily gain, G:F = gain-to-feed ratio, DOF = days on feed

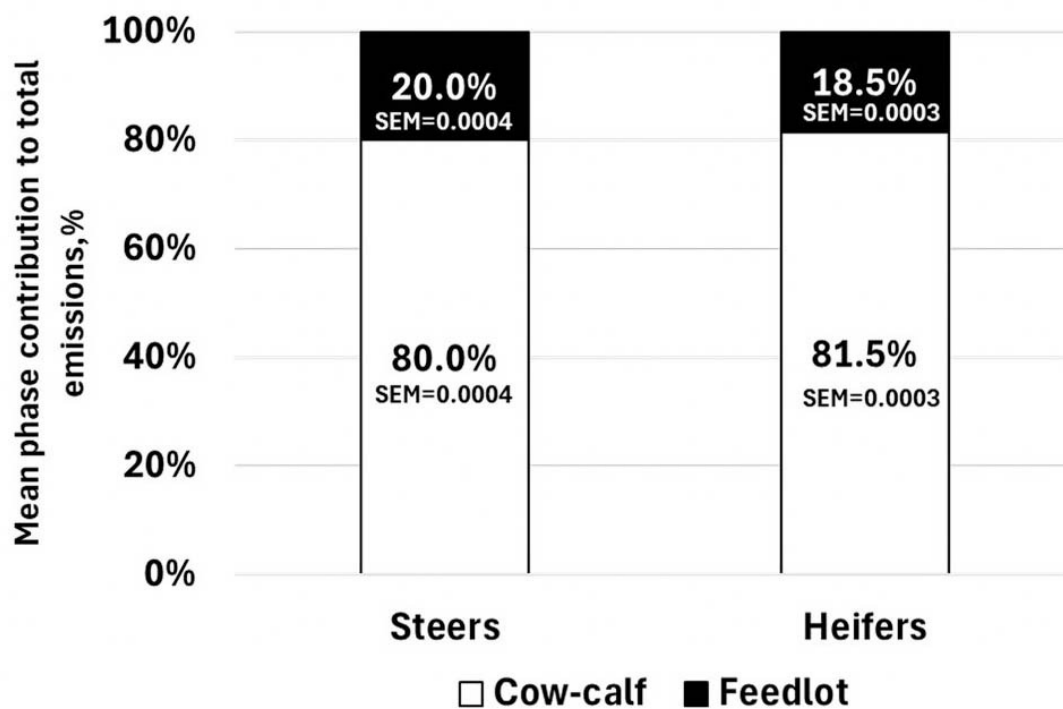


Figure 2.1. Crude pen-level means (and standard errors) for the percentage contribution of the cow-calf (white) and feedlot (black) phases to total estimated lifetime greenhouse gas (GHG) emissions, averaged across pens of feedlot steers and heifers.

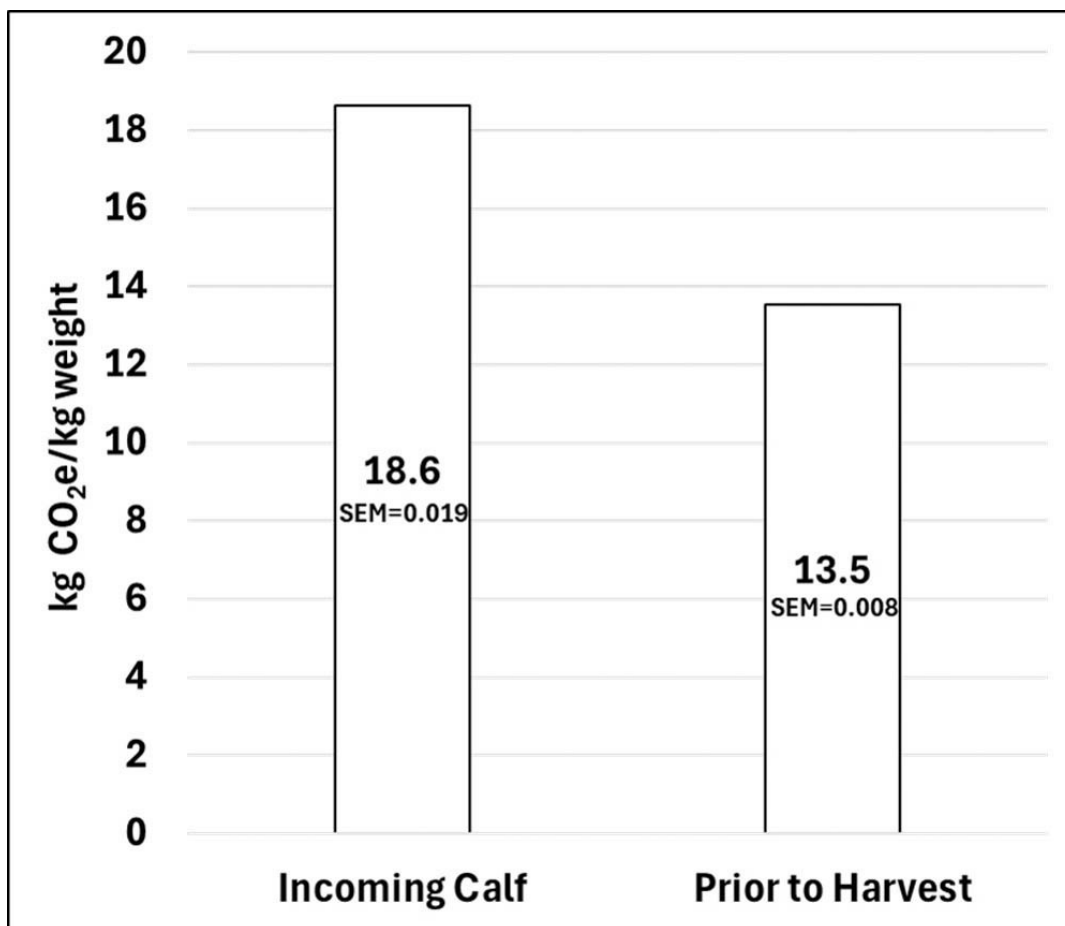


Figure 2.2. Crude pen-level means (and standard errors) for total lifecycle greenhouse gas (GHG) emissions intensity (kg CO₂e) per kg of body weight for cattle at two stages: upon arrival to the feedlot (incoming body weight) and immediately prior to harvest (final body weight).

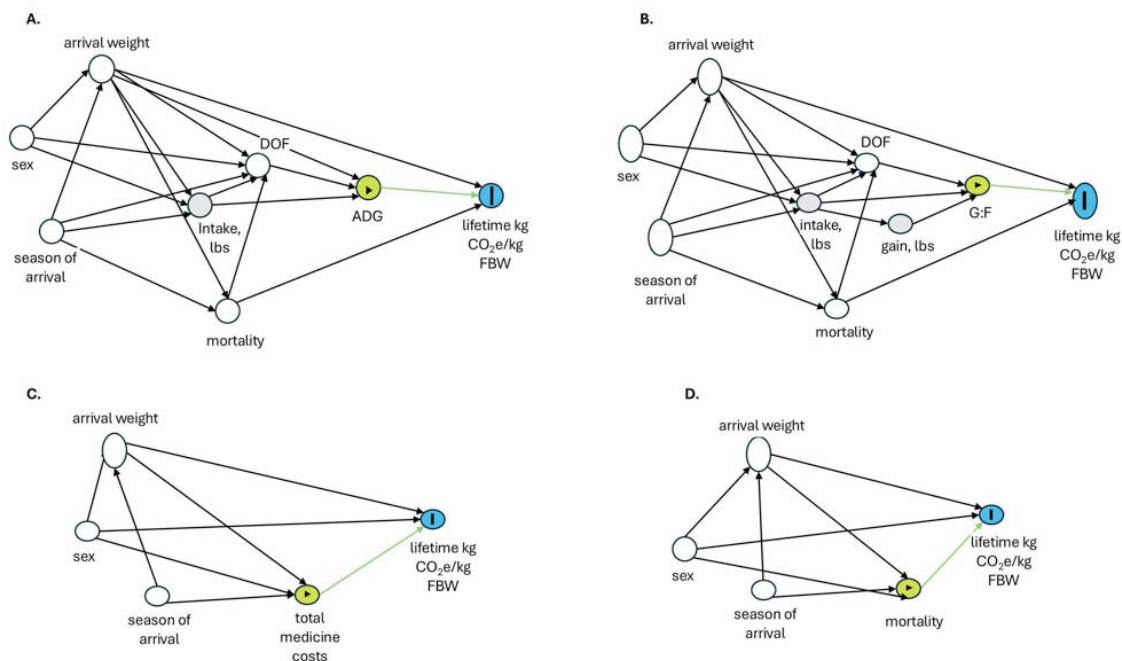


Figure 2.3. Directed acyclic graphs (DAGs) illustrating relationships between factors of interest and lifetime kg carbon dioxide equivalent emissions per kg of final body weight (lifetime kg CO₂e/kg FBW). A: This DAG illustrates the relationship between average daily gain (ADG) (exposure variable) and lifetime kg CO₂e/kg FBW (outcome variable). Potential confounders include sex of the pen (steers and heifers), season of feedlot arrival (Winter, January–March; Spring, April–June; Summer, July–September; Fall, October–December), days on feed (DOF), and arrival body weight class (227–272, 273–318, 319–363, 364–409, 410–454 kg). Intake (the amount of feed consumed over time) was included in the dataset but excluded from the model because it was not necessary to correctly adjust for direct and total effects. B: This DAG illustrates the relationship between feed efficiency (gain:feed ratio, G:F) and lifetime kg CO₂e/kg FBW. Potential confounders are the same as in A. Intake and pounds gained (the total weight gained during the feedlot phase) were included in the dataset but excluded from the model for similar reasons. C: This DAG focuses on total medicine costs (exposure variable) and lifetime kg CO₂e/kg FBW (outcome variable). Potential confounders include sex, season of feedlot arrival,

and arrival body weight. Sex is linked to both mortality and medicine costs, reflecting its role as a confounder. D: This DAG illustrates the relationship between cumulative mortality (exposure variable) and lifetime kg CO₂e/kg FBW (outcome variable). Potential confounders include sex, season of feedlot arrival, and arrival body weight. Sex is connected to mortality as a confounder. Black arrows indicate direct causal effects, while green arrows represent causal pathways. White circles denote adjusted variables, gray circles indicate variables excluded from the model but conceptually included in the analysis (e.g., intake, pounds gained), green circles represent exposure variables, and blue circles indicate outcome variables.

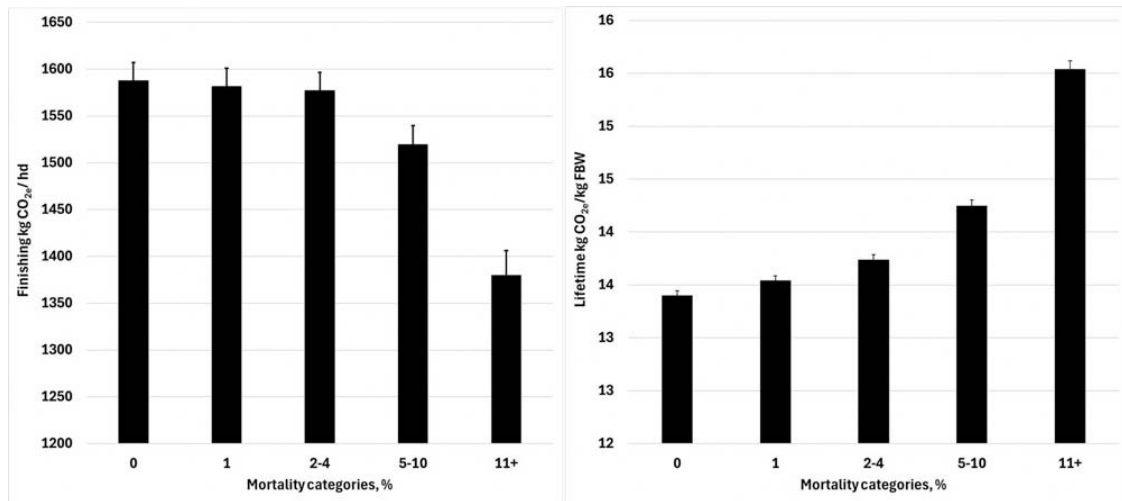


Figure 2.4. Model estimated means (and standard error of the mean) by cumulative pen mortality category for total finishing kg carbon dioxide equivalent emissions (CO_{2e}) per animal in the pen at feedlot arrival and lifetime kg CO_{2e} per kg of final body weight (FBW).

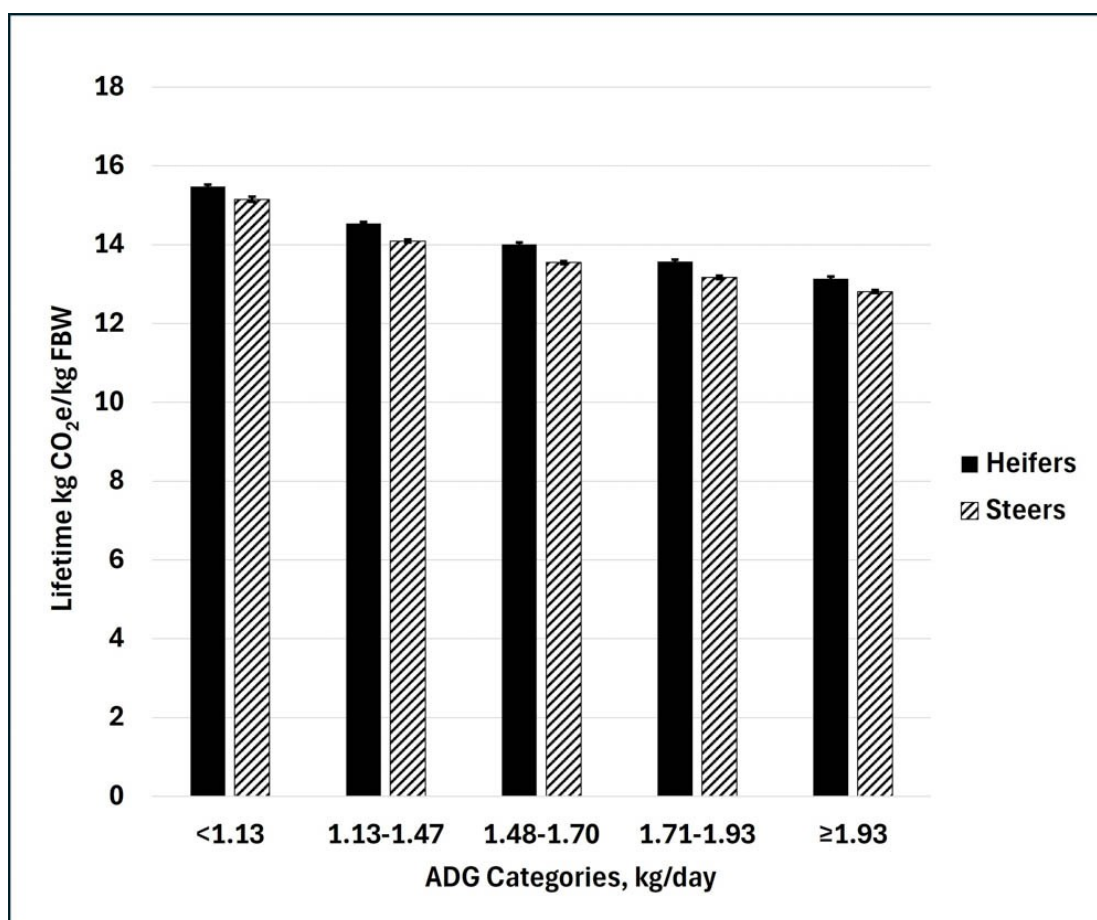


Figure 2.5. Model estimated means (and standard error of the mean) for kg carbon dioxide equivalent emissions (CO₂e) per kg of final body weight (FBW) by average daily weight gain (ADG) and sex of the pen (steers or heifers). The final multivariable model on the effect of ADG on estimated lifetime kg CO₂e/kg FBW included significant main effects of ADG, sex of the pen, and season of feedlot arrival. Potential confounding significant variables controlled in the model were cumulative mortality, arrival body weight, and days on feed. Significant interactions between ADG and sex of the pen (depicted here), and between ADG and season of feedlot arrival were also included.

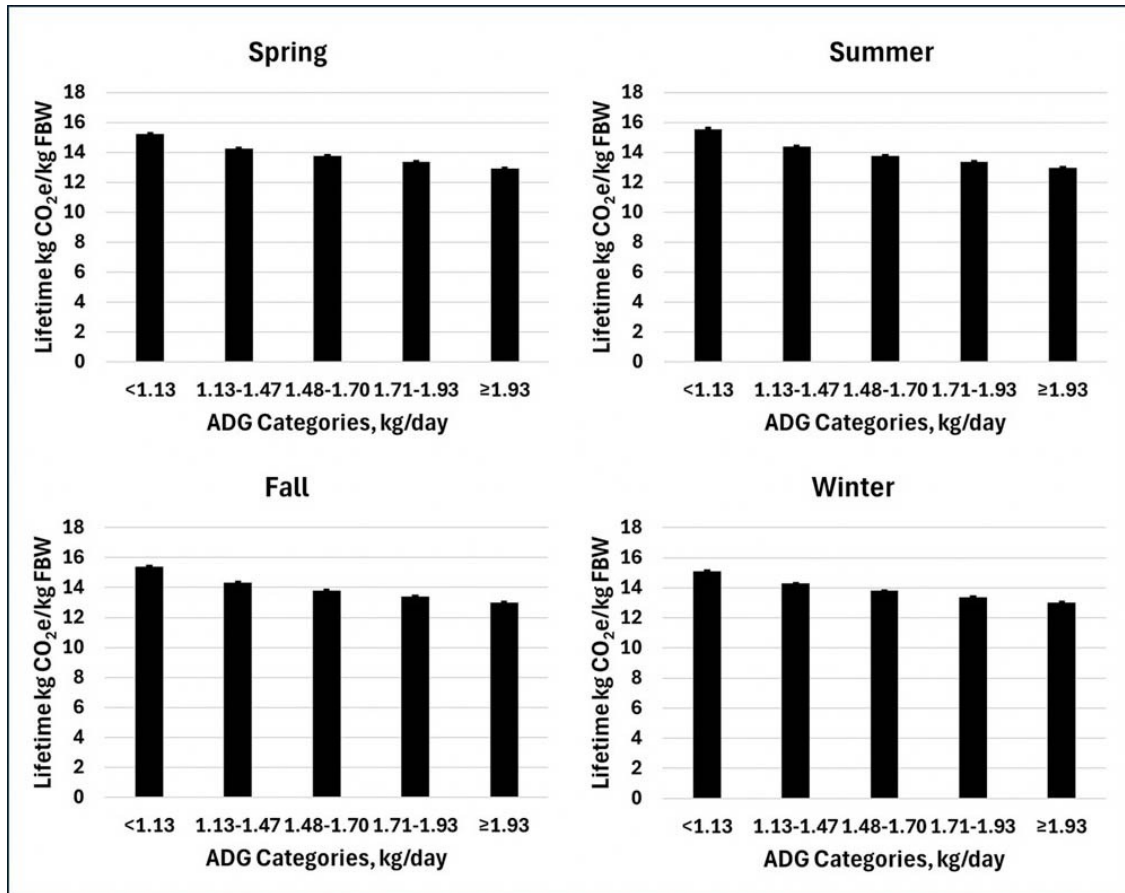


Figure 2.6. Model estimated means (and standard error of the mean) for kg carbon dioxide equivalent emissions (CO₂e) per kg of final body weight (FBW) for average daily gain (ADG) by season of feedlot arrival (Winter: January through March; Spring: April through June; Summer: July through September; and Fall: October through December). The final multivariable model analyzing the effect of ADG on estimated lifetime kg CO₂e/kg FBW included significant main effects of ADG, sex of the pen, and season of feedlot arrival, potential confounding variables of cumulative mortality, arrival body weight, and days on feed, and significant interactions between ADG and sex of the pen, and between ADG and season of feedlot arrival (depicted here).

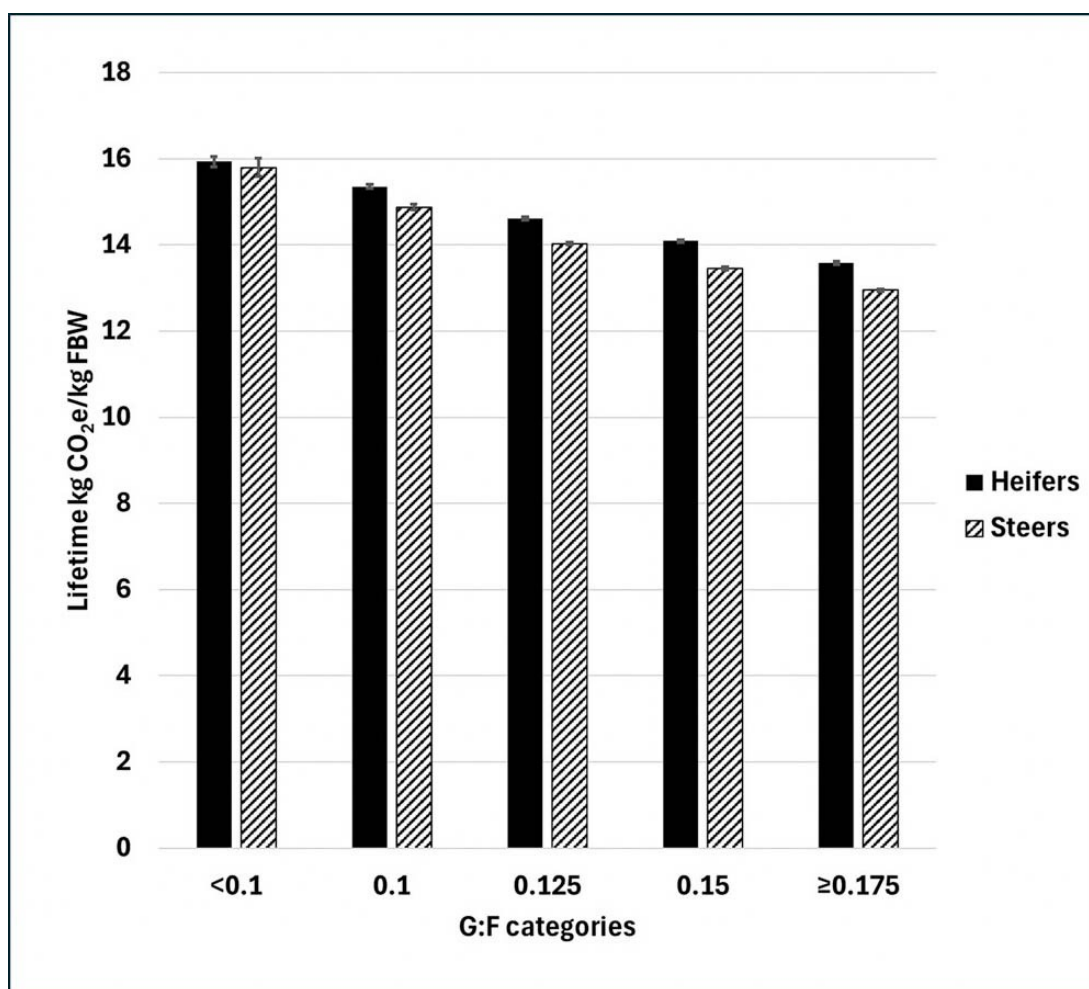


Figure 2.7. Model estimated means (and standard error of the mean) for kg carbon dioxide equivalent emissions (CO₂e) per kg of final body weight (FBW) for gain:feed (G:F) by sex of the pen (steers or heifers). The final multivariable model analyzing the effect of G:F on estimated lifetime kg CO₂e/kg FBW included significant main effects of G:F, sex of the pen, and season of feedlot arrival, potential confounding variables of cumulative mortality, arrival body weight, and days on feed, and significant interactions between G:F and sex of the pen (depicted here), and between G:F and season of feedlot arrival.

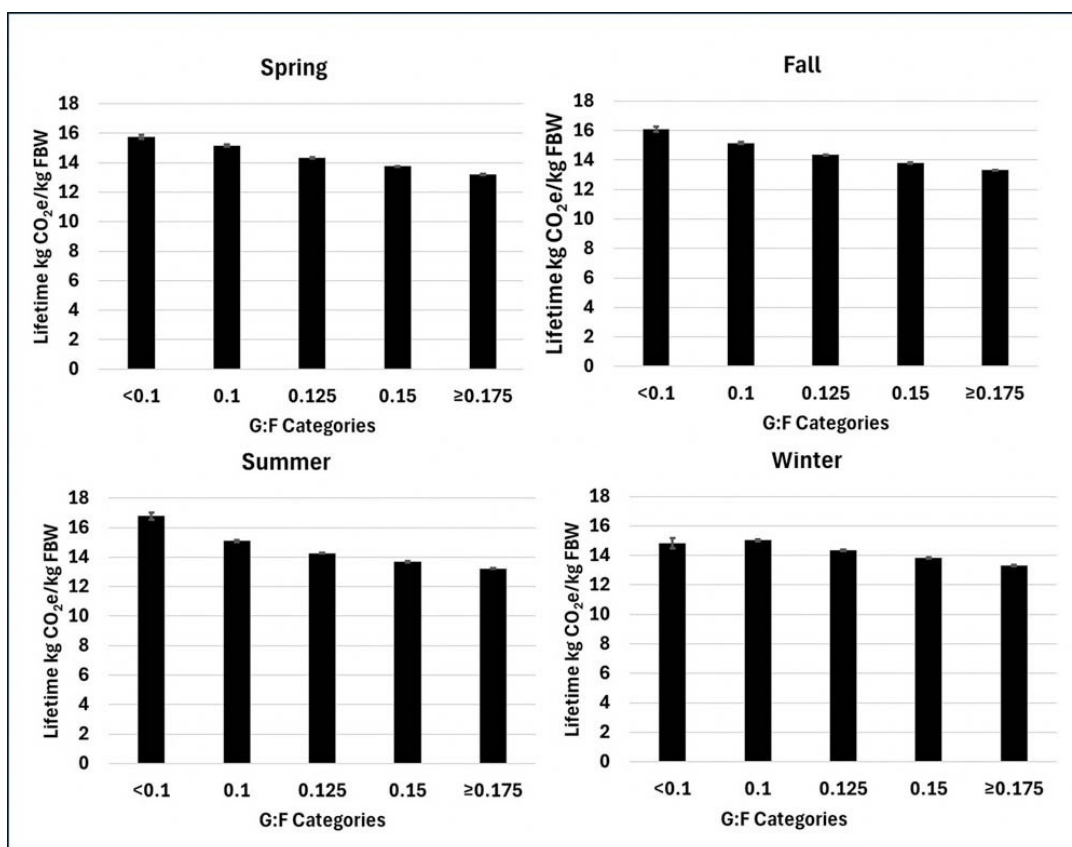


Figure 2.8. Model estimated means (and standard error of the mean) for kg carbon dioxide equivalent emissions (CO₂e) per kg of final body weight (FBW) for gain:feed (G:F) by season of feedlot arrival (Winter: January through March; Spring: April through June; Summer: July through September; and Fall: October through December). The final multivariable model analyzing the effect of G:F on estimated lifetime kg CO₂e/kg FBW included significant main effects of G:F, sex of the pen, and season of feedlot arrival, potential confounding variables of cumulative mortality, arrival body weight, and days on feed, and significant interactions between G:F and sex of the pen, and between G:F and season of feedlot arrival (depicted here).

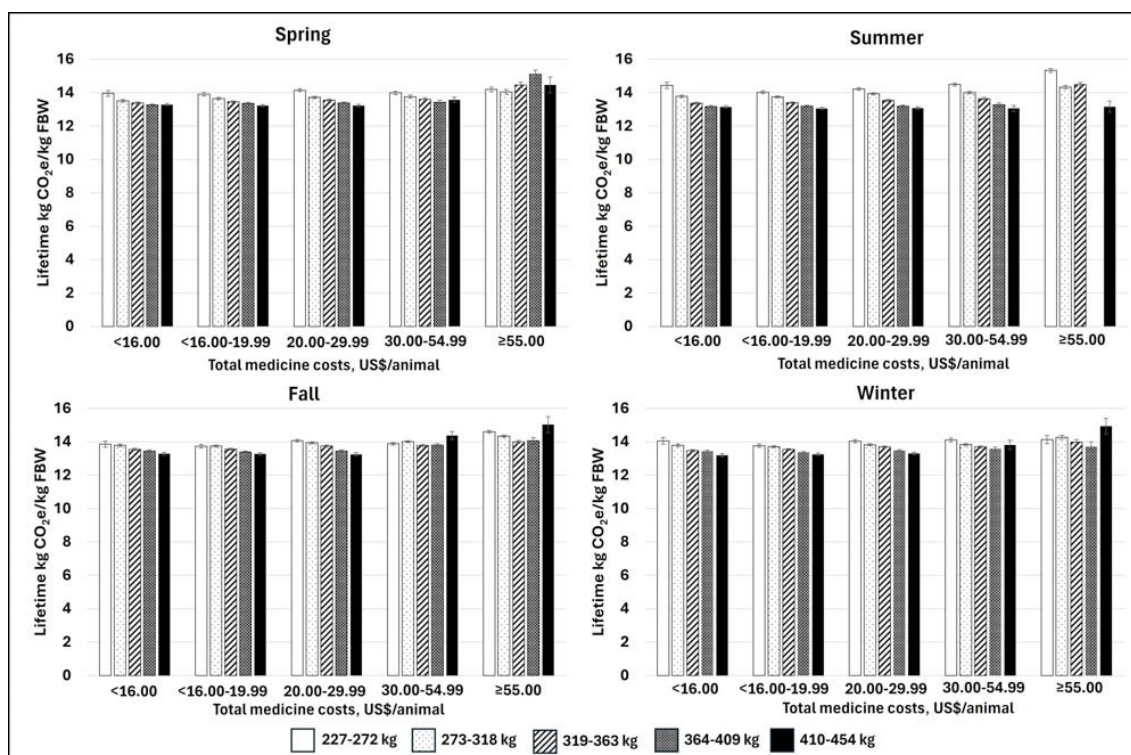


Figure 2.9. Model estimated means (and standard error of the mean) for kg carbon dioxide equivalent emissions (CO₂e) per kg of final body weight (FBW) by disease burden (total medicine costs, in US\$), arrival body weight class (227-272 kg, 273-318 kg, 319-363 kg, 364-409 kg, and 410-454 kg) and season of feedlot arrival (Winter: January through March; Spring: April through June; Summer: July through September; and Fall: October through December). The final multivariable model analyzing the effect of disease burden on estimated lifetime kg CO₂e/kg FBW included significant main effects of cumulative mortality, arrival body weight, and season of feedlot arrival, sex of the pen as a potential confounding variable, and significant interactions between cumulative mortality, season of feedlot arrival, and arrival body weight (depicted here).

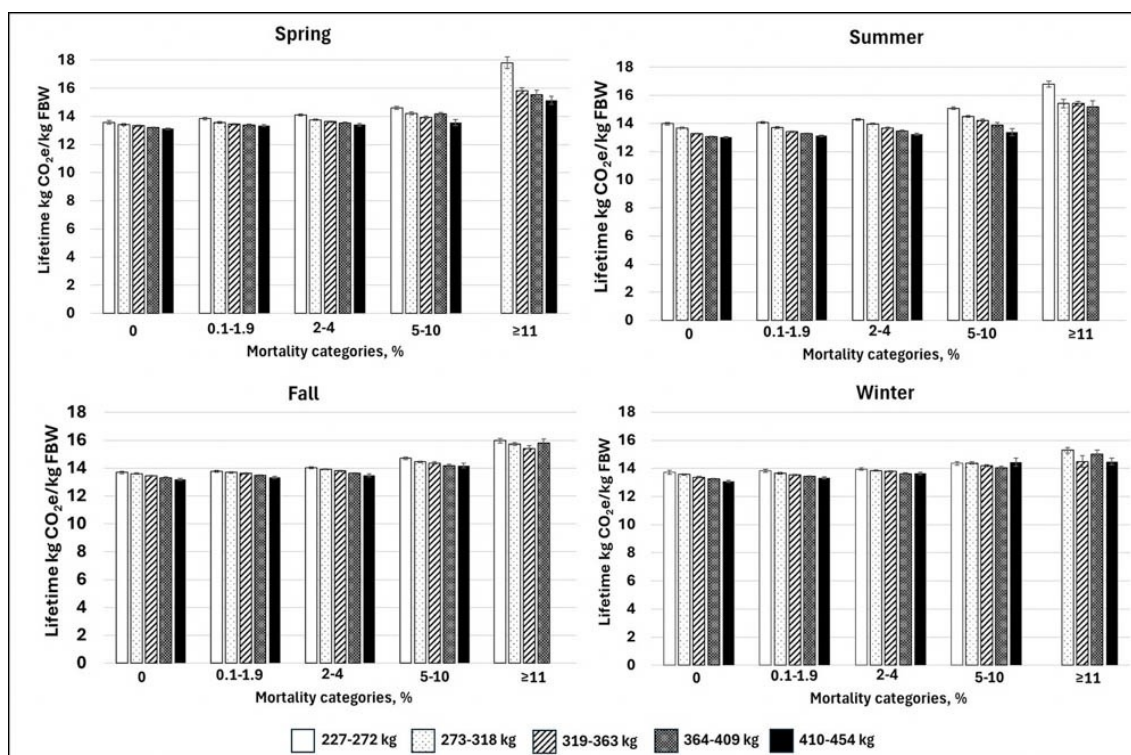


Figure 2.10. Model estimated means (and standard error of the mean) for kg carbon dioxide equivalent emissions (CO₂e) per kg of final body weight (FBW) by mortality category, arrival body weight class (227-272 kg, 273-318 kg, 319-363 kg, 364-409 kg, and 410-454 kg) and season of feedlot arrival (Winter: January through March; Spring: April through June; Summer: July through September; and Fall: October through December). The final multivariable model analyzing the effect of cumulative mortality on estimated lifetime kg CO₂e/kg FBW included significant main effects of cumulative mortality, arrival body weight, and season of feedlot arrival, sex as a potential confounding variable, and significant interactions between cumulative mortality, season of feedlot arrival, and arrival body weight (depicted here).

Chapter 3 - Cattle, carcass, economic, and estimated emission impacts of feeding finishing steers lubabegron or ractopamine hydrochloride

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Abstract

Lubabegron (Experior; Elanco, Greenfield, IN, USA) is the first U.S. Food and Drug Administration approved feed additive for reducing gas emissions from feedlot animals or their waste; it does not have live or carcass performance claims. Our primary objective was to determine the effect of lubabegron on feedlot performance and carcass traits in finishing beef steers compared to ractopamine hydrochloride (Optaflexx; Elanco, Greenfield, IN, USA). A commercial feedlot trial using cross-bred beef steers ($n = 2,117$; 373 ± 15 kg initial body weight

[BW]) was completed with a randomized complete block design. Treatments consisted of two feed additives: (1) OPT targeted to deliver 300 mg/animal/d of ractopamine hydrochloride for 28 ± 7 d out from harvest and (2) EXP targeted to deliver 36 mg/animal/d of lubabegron 56 ± 7 d out from harvest and a 4-d preslaughter withdrawal period. Twenty 70 to 142 hd pens with 10 pens per treatment were used. Cattle were weighed at arrival processing and at harvest and fed for an average of 167 d. Data were used to calculate production metrics, partial budgets, and estimated greenhouse gas emissions using published methods, and were analyzed using linear mixed models with pen as the experimental unit and block as a random intercept. A statistical significance threshold of $\alpha = 0.05$ was determined a priori. There was no evidence for statistically significant differences between treatments for initial BW ($P = 0.70$), health-related outcomes (P values ≥ 0.43), or mobility scores ($P = 0.09$). Cattle-fed EXP had increased final BW, ADG, G:F, and decreased dry matter intake (P values ≤ 0.01) compared to OPT. Carcasses were 11 ± 1.76 kg (hot carcass weight) heavier in EXP group ($P < 0.01$), and differed between treatments for both yield grades (YG) and quality grades distributions (P values ≤ 0.01). Cattle-fed EXP had a shift toward more YG 1 and 2, select and sub-select carcasses compared to OPT, which had a shift toward more YG 3, 4, 5, prime and choice carcasses. With increased beef production and efficiency compared to OPT, the estimated CO₂ equivalent emissions from production were reduced by 6.2% per unit of carcass weight for EXP ($P \leq 0.01$). Estimated net returns/animal shipped were $\$56.61 \pm 9.37$ more for EXP than OPT ($P \leq 0.01$). In conclusion, when cattle were fed for the same total number of days, feeding EXP compared to OPT increased net returns, feedlot performance, and efficiency, but resulted in carcass yield and quality characteristics that may impact marketing programs.

Key words: carcass traits, feedlot performance, greenhouse gas emissions, lubabegron, net returns, ractopamine hydrochloride

Lay Summary

Lubabegron (Experior), the first Food and Drug Administration approved feed additive for reducing gas emissions from feedlot animals, was studied for its impact on feedlot performance and carcass traits in beef steers compared to feeding ractopamine hydrochloride (Optaflexx). In a commercial feedlot trial with 2,117 cross-bred beef steers, lubabegron (EXP) demonstrated advantages over ractopamine hydrochloride (OPT) in final body weight, average daily gain, feed efficiency, and reduced dry matter intake. Carcasses from EXP were heavier, with shifts towards decreased yield and quality grades. The feeding of EXP resulted in a 6.2% reduction in estimated CO₂ equivalent emissions per unit of carcass weight, and a \$56.61 higher estimated net returns per animal shipped compared to OPT. This study indicates that feeding Experior instead of Optaflexx in commercial feedlot steers enhances feedlot performance and efficiency while influencing carcass characteristics that may impact marketing programs.

Introduction

Sustainability and efficiency of beef production are intertwined, with sustainability becoming an increasing interest for stakeholders in the beef industry. Though sustainability can be a broad concept, a simplified definition is that sustainable food production is a balance between environmental responsibility, economic viability, and social acceptability (de Wit et al., 1995; United Nations, 2005). Consumer and stakeholder attention to modern food production systems emissions has intensified (Teeter et al., 2021), particularly for greenhouse gas (GHG) emissions such as NH₃ (Brown et al., 2018). A new feed additive technology, lubabegron (Experior; Elanco, Greenfield, IN, USA, <https://elancolabels.com/us/experior-10>), is the first

U.S. Food and Drug Administration (FDA) approved feed additive for reducing gas emissions from an animal or its waste. Lubabegron is approved for reducing NH₃ gas emissions/kg final BW and kg hot carcass weight (HCW) when administered during the last 14 to 91 d on feed. It does not have label claims for impacting live animal or carcass performance.

Lubabegron is a selective β modulator, meaning that it is a β -adrenergic agonist and antagonist (FDA-FIO, 2018), and differs from beta-agonists like ractopamine hydrochloride (Optaflexx; Elanco, Greenfield, IN, USA). One large pen commercial feedlot study demonstrated feeding lubabegron, as compared to a negative control group, resulted in an increase in final body weight (BW) and hot carcass weight (Kube et al., 2021). This study also demonstrated no significant differences in morbidity, animal removals, or mortalities. Additionally, there was no evidence for differences in cattle mobility between treatments. To date, there are no published studies comparing lubabegron to a beta-agonist.

Our primary objective was to determine the effect of lubabegron on live performance and carcass traits in finishing beef steers compared to ractopamine hydrochloride. Secondary outcomes of interest included health outcomes, mobility scores, economic returns, and emissions estimates. Our null hypotheses were that there were no differences in observed performance, carcass, health, mobility, economic, or emission outcomes. This is the first published large pen commercial feedlot comparison of lubabegron and ractopamine hydrochloride in beef steers.

Materials and Methods

The experimental phase of the trial was initiated on August 2, 2022, and completed on February 10, 2023, in central KS. All study procedures were reviewed and approved by Kansas State University's Institutional Animal Care and Use Committee (Approval number IACUC-4785).

Experimental Design

A controlled trial in a randomized complete block design was carried out using cross-bred beef steers ($n = 2,081$). Experimental treatments consisted of two different feed additives (1) OPT targeted to deliver 300 mg/animal/d of ractopamine hydrochloride for 28 ± 7 d prior to harvest and (2) EXP targeted to deliver 36 mg/animal/d of lubabegron 56 ± 7 d prior to harvest and a 4-d preslaughter withdrawal period. Treatments were randomly assigned to a pen within a block, and each block represented a single replication of each treatment. Steers were from a single source and blocked by arrival date. Twenty total pens, with 10 pens per treatment were used. Steers were allocated into one of the two pens within a block by sorting five animals at a time until the desired number of animals was reached for each pen. Once filled, pens were weighed in drafts on a platform scale to determine initial BW. Pens were randomly assigned to treatment using the RAND function of Excel (Microsoft, Redmond, WA, USA). Sample size estimates using $\alpha = 0.05$, $\beta = 0.185$, and historical baseline data from the commercial feedlot indicated 10 blocks (2 pens per block, 20 pens) were necessary to demonstrate a 0.06 difference in the probability of carcasses having a quality grade of choice or better. The number of animals per pen were fixed based on the feedlot space per pen but influenced the precision of pen-level estimates for sample size calculations. Aside from treatments administered, all feedlot procedures (including processing, handling, feeding, treating, and harvesting) were consistent for both pens within a block.

Cattle Management, Processing, and Housing

Receiving

Cross-bred beef steers were received between August 2nd and 22nd, 2022, and were sourced from a single ranch in KS. Upon arrival, steers were offered ad libitum

access to long-stemmed hay and water. Animals appearing maladjusted, over- or under-conditioned, having behavioral, disease, or appetency problems or conditions were removed from study candidacy.

Processing

After allocation and randomization to experimental pens, steers were processed in accordance with standard feedlot procedures. Processing products and amounts varied slightly but were consistent for pens within a block. At initial processing steers received: an ear tag with a lot number unique to each pen, an ear tag with a number unique to each animal, a five-way viral vaccine (Bovi-Shield Gold 5 [2 mL]; Zoetis Animal Health, Parsipany, NJ) administered subcutaneously (SC), a SC injection of an internal parasiticide (Dectomax [8 or 9 mL]; Zoetis Animal Health), an oral anthelmintic (Safeguard [19, 20, or 23 mL]; Merck Animal Health, DeSoto, KS), and an implant administered SC in the ear containing 100 mg trenbolone acetate and 14 mg estradiol benzoate (Synovex Choice; Zoetis Animal Health). Six pens of steers (all pens in blocks 8, 9, 10) were administered a pour-on insecticide, pyrethroid with IGR (Clean-Up II [30 mL]; Elanco Animal Health). After an average of 84 d on feed (range of 73 to 99 d; identical within blocks), steers received a terminal implant administered SC in the ear containing 200 mg trenbolone acetate and 28 mg estradiol benzoate (Synovex Plus; Zoetis Animal Health).

Housing

Pens were dirt-surfaced, of steel pipe construction, with open-air exposure, and measured on average 2,001 m² (range of 1,255 to 2,508 m²) which provided on average 19 m²/animal (range of 15 to 25 m²/animal). Average bunk space per animal was 30.86 cm (range of 25.73 to 36.14 cm). Pens within a block were adjacent to one another and

provided similar pen and bunk space per animal. Pens were equipped with an automatic water fountain allowing ad libitum access to fresh well water.

Animal health

All steers were observed daily by experienced animal caretakers that were blinded to treatment group. Steers exhibiting signs of abnormal health (e.g., lameness, depression, anorexia, and respiratory distress) were treated in accordance with feedlot protocols. If pulled from the home pen to a hospital pen, animals were further evaluated. Diagnostics performed chute-side included measurements of BW, rectal temperature, and lung auscultation scores via stethoscope. Steers were then treated according to protocols established by consulting veterinarians based on clinical signs from the pen and chute-side evaluations. In general, steers were treated and returned to home pens on the same day. If an animal required additional recovery time, it could reside in a hospital pen for a maximum of 10 d; if on the 10th d the animal was deemed unfit to return home they would then be removed from the study. Additionally, steers that failed to respond or were unlikely to respond to therapeutic treatment were removed from the study by personnel blinded to treatment groups.

Diet Preparation and Feeding

Diet formulations are described in Table 1. The finishing diet composition was the same for both treatment groups except for the experimental products (EXP and OPT). The finisher diet was formulated to provide 15.91% crude protein, 0.64% calcium, 0.42% phosphorous, 2.19 Mcal/kg net energy for maintenance, and 1.51 Mcal/kg net energy for gain. For the final 28 d ractopamine hydrochloride was included at a target rate of 300 mg/animal/d for OPT and lubabegron was included at a target rate of 36 mg/animal/d for

the final 53 d (52 to 54). Daily feed deliveries were summed at the pen level over the feeding period on a dry matter basis and divided by animal days to estimate mean daily dry matter intake (DMI) per animal. Animal-days is the number of cattle multiplied by the total number of days cattle were in the pen, including animal removals and mortalities up until the day of removal or death.

Harvest

On the day of harvest, pens within a block were weighed sequentially in drafts on a platform scale for measurement of final BW and a 4% shrink was applied. Steers were then loaded on trucks and transported approximately 193 km to a commercial abattoir in KS. Steers remained separate by pen throughout shipping and harvest. Mobility scores were collected at the processing plant by trained personnel from a consulting group who were blinded to treatment group. The mobility scoring systems categorized mobility as 1 = normal, walks easily, no apparent lameness or change in gait; 2 = exhibits minor stiffness, shortness of stride, slight limp, still keeps up with normal cattle; 3 = exhibits obvious stiffness, difficulty taking steps, obvious limp, obvious discomfort, lags behind normal cattle; and 4 = extremely reluctant to move even when encouraged by a handler; statue-like (NAMI 2015). Additional variables collected by trained and blinded personnel included HCW, USDA quality grade (QG), USDA yield grade (YG), 12th-rib fat thickness, longissimus muscle area, marbling score, and calculated yield grade. Non-weight measurements were determined with a video image analysis system. Average dressing percentage for each pen was calculated as the total HCW divided by shrunk final BW.

Economic Assessment

A partial budget was used to evaluate treatment effects on economic returns of feedlot steers using pen-level cumulative (close-out) data from the entire feeding period. Cost parameters in the partial budget were: cattle purchases, processing, treatment antimicrobials, rendering fees (for mortalities), feed, and yardage (accounts for labor and facilities maintenance). Revenue from cattle sales was evaluated on the bases of both live (non-adjusted) sales and dressed sales adjusted for carcass quality-based premiums and discounts. Revenue parameters in the partial budget were: culled animals (sale of animals removed from trial), live cattle sales, and dressed cattle sales adjusted for YG, QG, and over- or under-weight carcasses. A net return value was calculated for each pen, where net return is the difference between total revenue and total variable expenses for that pen. Net returns are the final outcome of the partial budgets.

Cattle purchase price was \$174.24/ 45.4 kg (100 lb), and was multiplied by the total initial BW of each pen. This price was the average of weekly prices from the range of dates that animals were enrolled (August 2 to August 22, 2023), sourced from the Livestock Marketing Information Center, Oklahoma City Auction, for medium and large frame #1 feeder steers weighing 364 to 409 kg (800 to 900 lb). The total feed consumed by each pen was multiplied by monthly prices for dry feed, feed markup, and yardage from the Central Plains region, which were averaged into a mean price of \$406.95/ 907 kg (2000 lb) dry feed (CattleFax, 2022).

Standardized processing costs were used for all blocks, where products and prices were sourced from PBS Animal Health on December 15, 2022, and dosage to estimate price/animal was calculated based on manufacturer recommendations and a 364 kg animal weight. The processing products and prices per animal were: a modified-live antiviral vaccine at \$1.50/animal (Bovi-shield Gold 5, Zoetis), an oral anthelmintic at \$1.93/animal (Safeguard, Merck

Animal Health), an injectable parasiticide at \$2.47/animal (Dectomax, Zoetis Animal Health, Parsippany, NJ), a topical insecticide at \$0.97/animal (Clean-up_II, Elanco Animal Health, Greenfield, IN), two ear tags for identification at \$1.99/animal (ATag, Allflex, Kenilworth, NJ), initial implant at \$3.13/animal (Synovex Choice, Zoetis), a re-implant at \$3.82/animal (Synovex Plus, Zoetis), and an assumed \$1.50/animal chute charge for equipment and labor at both initial processing and re-implant. The total processing cost per animal was \$18.82.

Morbidity costs were estimated at \$23.60/treatment charge (USDA-NAHMS, 2013) and were multiplied by the number of animal treatments in each pen. An estimated cost for rendering a dead animal was used for all dead animals, at \$38.24 (Horton et al., 2023). As described by Horton et al., 2021, a percentage of the national dressed breaker cow (over 227 kg) price was used to estimate revenue from animals removed from the trial. Averaged national dressed Breaker cow prices from the USDA—Agricultural Marketing Service (AMS; USDA-AMS LM_CT168, 2023) based on the range of block harvest dates was \$153.99/45.4 kg. A regression provided by Tatum et al. 2012, was used to estimate the HCW of removed animals. A percentage of the Breaker cow price was multiplied by the total removed animal HCW from each pen based on HCW category (Horton et al., 2021).

The price for the live sale scenario was \$157.77/45.4 kg multiplied by the total shrunk pen BW for estimated revenue for live cattle sales. These numbers are representative values of steers expected to grade over 80% choice, and sold live (free-on-board) based on the average weekly prices of the timeframe the steers were harvested (USDA-AMS LM_CT150, 2023). For dressed-fed cattle sales, the base price was the live-fed price stated above divided by a common 63.5% dressed yield, or \$248.46/45.4 kg. Using carcass-based premiums and discounts (YG, QG, and weight) the base dressed revenue was adjusted by using an average of prices reported

by the USDA-AMS (USDA-AMS LM_CT169, 2023). The premiums per 45.4 kg for Prime, YG 1, and YG 2 carcasses were \$24.20, \$5.10, and \$2.10, respectively. The discounts per 45.4 kg for Select, Standard, YG 4, YG 5, HCW under 249 kg, and HCW over 476 kg were −\$22.60, −\$34.60, −\$10.10, −\$13.80, −\$30.80, and −\$16.70, respectively. The total revenue from animals sold on a dressed basis was calculated by multiplying the premium and discount prices with the total pen HCW that fell in each category (e.g., Prime price multiplied by Prime HCW). These additions and subtractions from the base dressed revenue contributed to the overall total revenue for the pen. The parameters and prices used in the partial budget are in Appendix Table A.

Production Emissions

As described in the study by Horton et al. (2023), the Uplook 1.0 (Elanco Animal Health) system was used to estimate emissions based on calculated carbon dioxide equivalents (CO₂e). These calculations for greenhouse gas emissions from agricultural practices incorporate methodologies from the U.S. Department of Agriculture USDA (2014), the Intergovernmental Panel on Climate Change (Dong et al., 2019), and the U.S. Environmental Protection Agency (EPA; US EPA, 2022). Briefly, incoming calf estimates were assumed to represent the carbon footprint of animals prior to their arrival at the feedlot. Breed and initial BW were primary factors for incoming calf estimates in addition to estimated enteric methane, manure, fertilizer used for pastures, supplemental feed, and on-farm fuel and electricity usage, including for cattle transport to the feedlot. For this study, these were identical values for animals with equal BW. Differences in BW were assumed to represent differences in days of life (and emissions) prior to the feedyard. The feedlot model inputs were based on data from the feedlot trial and included feed impacts, feedlot energy use, methane and nitrous oxide from manure, animal enteric methane, *n* animals enrolled, total initial BW, animal days, animal removals and mortalities, *n*

final animals, final BW, and HCW. The final values of CO₂e were described per unit of beef production (live BW and HCW), and per animal enrolled (Horton et al, 2023).

Statistical Analyses

Data were analyzed as a randomized complete block design. For all analyses pen was the experimental unit with cumulative pen-level outcome data from the entire feeding period to reflect common measures used in commercial feedlots (close-outs). The fixed effect was treatment (EXP or OPT) and block was included as a random intercept term. General and generalized linear mixed models (Proc GLIMMIX SAS 9.4; SAS Institute Inc., Cary, NC) were fit to evaluate treatment effects on response variables of interest. Continuous outcomes (BW, ADG, DMI, and G:F; performance and non-categorical carcass data) were analyzed using linear mixed models. Morbidity and mortality measures were analyzed with binomial distributions and a logit link function with the same fixed and random effects. Categorical (YG, QG, and MS) data were analyzed similarly, but with multinomial distributions and a cumulative logit link function accounting for the ordinal responses (Osterstock et al., 2010). Additionally, data on daily DMI during the last 59 d pre-harvest was evaluated using a linear mixed model with fixed effects of day, treatment, and treatment $\times$ day, and an autoregressive covariance structure to account for repeated measures (within blocks) on pens over time. Model-adjusted means and standard errors are reported (following back-transformation for generalized models). For all analyses, significance was declared between treatments at $\alpha \leq 0.05$.

Results

There was an average of 105 steers/pen (range of 70 to 142). Six pens (3 blocks) were harvested on January 12th, 2023; eight pens (four blocks) were harvested on January 19th, 2023; and the remaining six pens (three blocks) were harvested on February 10th, 2023. The average

days on trial was 167 and ranged from 157 to 172. Initial BW did not differ significantly between treatments ($P = 0.70$).

Health and Mobility

There was no evidence of a difference between treatments for any measured health outcomes during the entire feeding period (Table 2); this includes morbidity treatment categories including respiratory, digestive, and other (all $P \geq 0.34$). Mortalities of all categories (respiratory, digestive, other) were not significantly different between treatments either ($P \geq 0.61$). Total removals, both animals that died and those that were removed from the study for health reasons, were 1.61% for EXP and 1.70% for OPT ($P = 0.89$). The animal mobility results are also summarized in Table 2. The distributions of mobility scores for each treatment did not differ significantly ($P = 0.09$). A vast majority of all animals had a score of 1 (2,005/2,081), and over 99% of all animals in the trial scored a 1 or 2 (2,066/2,081).

Feedlot Performance

Feedlot growth performance characteristics are outlined in Table 3. BW gain and feed conversion metrics were calculated using two methods; (1) with dead and removed animals excluded (DRO) and (2) with dead and removed animals included (DRI). Overall, growth performance was improved (P values < 0.05) in cattle receiving EXP compared to OPT (Table 3). Using DRO calculations, final BW increased by 9 kg ($P < 0.01$), ADG increased by 3.26% ($P < 0.01$), DMI decreased by 3.67% ($P = 0.01$), and gain efficiency improved by 6.59% ($P < 0.01$) for cattle receiving EXP compared to OPT (Table 3). During the last 59 d pre-harvest, daily DMI was significantly associated with the main effects of treatment ($P < 0.01$; EXP = 10.68 ± 0.138 , OPT = 11.05 ± 0.138) and study day ($P < 0.01$), but there was no evidence ($P = 0.92$) for treatment by day interaction. Using DRI calculations ADG increased 2.25% ($P = 0.03$), DMI

decreased 3.64% ($P = 0.01$), and gain efficiency improved 6.06% ($P < 0.01$) in cattle receiving EXP compared to OPT (Table 3).

Carcass Characteristics

Carcass characteristics are summarized in Table 4. There were differences between treatments for all outcomes except for 12th-rib fat thickness ($P = 0.13$). HCW increased by 10.92 kg ($P < 0.01$), dressing percentage increased by 0.72% ($P < 0.01$), REA increased by 4.51cm² ($P < 0.01$), marbling score decreased 23 units (Table 4; $P < 0.01$), and calculated YG decreased 0.19 points ($P < 0.01$) for cattle receiving EXP compared to OPT.

Yield grade distributions were different ($P = 0.01$) between treatments. The EXP cattle had greater frequency of YG 1, 2, and 3 carcasses compared to OPT, while YG 4 and 5 carcasses were fewer. Quality grade distributions were evaluated using two different methods; (1) using the QG reported by the packing plant or (2) using QG based on marbling score. The latter was done to evaluate upper 2/3 and bottom 1/3 choice distributions. For both methods, the quality grade distributions differed ($P < 0.01$) between treatments. The shifts in the distributions were similar for both methods, where cattle receiving EXP had fewer Prime and Choice carcasses and more Select and sub-select carcasses compared to cattle receiving OPT. Cattle receiving EXP had fewer Prime and Upper 2/3 Choice carcasses, and more Bottom 1/3 Choice, Select, and sub-Select carcasses compared to cattle receiving OPT.

Economic Assessment

Results from the partial budget comparisons between the treatments are in Table 5, where the main budgetary components are shown. The average purchase price per animal did not significantly differ between treatments ($P = 0.70$), due to similar initial BW (Table 5). The OPT cattle had increased feed and yardage costs of almost \$31 per animal enrolled ($P = 0.02$). On a

live sale basis, EXP cattle received approximately \$24 more revenue per animal ($P = 0.03$), and approximately \$31 more per carcass ($P < 0.01$) compared to OPT on a dressed sale basis. The average net return for EXP cattle was almost \$61 more than OPT ($P < 0.01$) on a dressed sale basis, and nearly \$57 more than OPT ($P < 0.01$) on a live sale basis.

Production Emissions

The calculated estimates of carbon dioxide equivalent (CO₂e) emissions from various sources linked to trial cattle production are displayed in Table 6. In the pre-feedlot, calf production phase there was no evidence of a difference in estimated CO₂e emissions ($P = 0.66$) due to the identical sources and similar initial BW of animals between treatments. For both the feedlot phase and the total lifecycle CO₂e emissions, the OPT cattle generated more estimated CO₂e emissions (per animal enrolled) than the EXP cattle ($P \leq 0.02$). In the finishing phase, OPT-fed cattle produced more estimated CO₂e emissions in feedlot operations ($P = 0.03$; includes emissions associated with the production of dry feed ingredients, commodity trucking, and fuel and utilities), manure ($P = 0.01$), and enteric methane ($P = 0.02$) compared to EXP fed cattle. In total, the factors contributing to the feeding phase emissions resulted in an estimated 69.3 kg more CO₂e emitted for OPT cattle than EXP ($P = 0.02$). Thus, subsequent differences were observed for the total finishing period CO₂e per kg of final BW ($P < 0.01$) and HCW ($P < 0.01$). Finally, the total lifecycle CO₂e estimated emissions were greater for OPT than EXP per animal enrolled ($P < 0.01$), per unit of final BW ($P < 0.01$), and HCW ($P < 0.01$; Table 6).

Discussion

This first publication on commercial feedlot steers fed lubabegron or ractopamine hydrochloride demonstrated significant differences in multiple outcomes of importance to the industry. Lubabegron has no claims for increasing the performance of steers, only for reducing

ammonia emissions, yet several important performance differences were demonstrated here. Ractopamine hydrochloride has performance claims of increased rate of weight gain, improved feed efficiency, and increased carcass leanness, but those are in comparison to a negative control.

The approval for the use of lubabegron was completed in two clinical registration studies at differing days (14 or 91) and feeding dosages (1.4 or 5.5 mg·kg⁻¹; FDA-FOI, 2018). The first commercial large pen trial evaluated the health and performance outcomes of cattle fed differing dosages of lubabegron (0, 1.4, 3.5, or 5.5 mg·kg⁻¹) during the last 56 d of the feeding period (Kube et al., 2021). Though the previous studies evaluated different dosages and days of feeding lubabegron, as opposed to comparing to a different product as in the current study, similar outcomes were identified for cattle-fed lubabegron. Previous studies also demonstrated no significant adverse health effects associated with feeding lubabegron (FDA-FOI, 2018; Kube et al., 2021). Cattle mobility was a concern with the expected increased final BWs and was evaluated with the same mobility scoring system used here (NAMI, 2015) in the first commercial large pen study (Kube et al., 2021), which also demonstrated that mobility did not differ significantly between treatments. Factors that have been attributed to fed cattle mobility issues include the intensity of handling, heat stress, transportation and lairage conditions, and subclinical laminitis, in addition to increased slaughter weights and DOF (Bernhard et al., 2014; Burson, 2014; Boyd et al., 2015; Thomson et al., 2015; Hagenmaier et al., 2017a, 2017b; Mijares et al., 2021).

As this is the first known published paper describing a comparison of lubabegron and ractopamine hydrochloride, available literature for comparison is minimal. Though there are no label claims for animal performance for lubabegron, both this study and previous studies (FDA-FOI, 2018; Kube et al., 2021) found an increased BW and HCW for steers fed lubabegron as

compared to a negative control or steers fed ractopamine hydrochloride. The previous large pen study also demonstrated a dose–response, where an increasing dosage of lubabegron fed during the last 56 d of the feeding period increased dressing percentage and decreased marbling score, yield grade, and quality grade (Kube et al., 2021). Additionally, performance outcomes for cattle-fed lubabegron compared to a control in a previous large pen study included greater DMI, ADG, and G:F (Kube et al., 2021). The current study had similar outcomes as Kube et al. (2021) for ADG, G:F, health outcomes, and carcass characteristics, but for EXP compared to OPT rather than compared to a negative control. However, a lower DMI was observed in this study for the lubabegron-fed cattle. When the daily DMI data were evaluated for the last 59 d on feed, the results demonstrated that the difference in the pen-level cumulative (close-out) DMI data from the entire feeding period (Table 3) was not due to an interaction of DMI by days at the end of the feeding period. These results demonstrate that lubabegron can increase animal growth performance, even when being compared to a product that is specifically labeled for growth performance.

The increased net returns for EXP cattle were primarily due to less feed consumed and increased BW and HCW, which also had a positive impact on estimated emissions. In a previous trial, the lubabegron label claim for reduced ammonia emissions was verified with calculated estimated ammonia emissions (Kube et al., 2021) and demonstrated that feeding lubabegron compared to a negative control resulted in decreased ammonia emissions. Although the emissions in this study were estimated CO₂e and there was a different treatment group for comparison, the CO₂e estimates from this study also show decreased emissions compared to ractopamine hydrochloride.

Distinctions in the mechanism of action between lubabegron and ractopamine hydrochloride may explain the observed differences in performance outcomes. While lubabegron has a core structure of phenylethanolamine, ractopamine hydrochloride exhibits a phenethanolamine moiety structure (Dilger et al., 2021). Lubabegron binds and activates β_3 receptors found in muscle and adipose tissue and throughout the body but acts as an antagonist to β_1 and β_2 receptors (FDA-FOI, 2018). In contrast, ractopamine hydrochloride only binds to β_1 and β_2 receptors throughout the body including muscle and adipose tissue (FDA-FOI, 2003).

This study was limited to a single feedlot, in one geographic region, with a specific cattle type. While these results may be representative of cross-bred beef steers fed in Central KS, extrapolating these findings to other cattle types, heifers, and different geographic areas necessitates further investigation. Furthermore, the number of days from harvest in which lubabegron may be fed is variable and could subsequently result in variation in observed outcomes.

Lubabegron (Exterior) is a new β -modulator feed additive on the market and the potential effects on carcass characteristics, animal performance, mobility, and health and are of interest. There was no evidence that lubabegron had any negative impacts on cattle health or mobility. However, there were important differences between treatments for live and carcass performance. The EXP treatment led to noteworthy enhancements in numerous live performance parameters including FBW, ADG, and DMI, when compared to OPT. In addition, several important carcass attributes were affected, particularly regarding leanness and the distributions of yield and QG. These differences in yield and quality grade distributions could have important implications on a beef producer's grid specifications, total DOF, and targeted FBW. Furthermore, a noteworthy potential environmental implication was observed with a reduction of

estimated CO₂e emissions. Thus, EXP has the potential to enhance cattle performance and economic gains, as well as mitigate the carbon footprint associated with cattle production.

Conclusion

In conclusion, when cattle were fed for the same total number of days, feeding EXP compared to OPT increased net returns, feedlot performance, and efficiency in live animals, but resulted in carcass yield and quality characteristics that may impact beef marketing programs. These observed shifts in outcomes potentially could be altered by manipulating the duration of feeding EXP and/or the total DOF. Considering the potential impacts of feeding EXP, it appears prudent to conduct further research aimed at optimizing a specific set of end-point criteria such as HCW and grid marketing targets to harness the potential benefits.

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Conflict of Interest Statement

One author (NB) is an employee of Elanco Animal Health, but he had no role in the design or implementation of the study; he calculated estimated emissions for de-identified lots (i.e., was masked to treatments). Other authors (DR, BD) have previously received funding from Elanco Animal Health for research or consulting work.

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Tables

Table 3.1. Dietary ingredient formulations and calculated nutrient composition of the finishing diet fed to feedlot steers during the experimental period

Item	Finisher [†]
Ingredient, % dry matter	
Steam-flaked corn	71.66
Wet distillers grain	16.67
Corn silage	7.25
Liquid supplement	4.40
Micro ingredients [‡]	0.02
Nutrient Composition	
Dry matter, %	58.75
Crude protein, %	15.91
Fat, %	4.50
Calcium, %	0.64
Phosphorus, %	0.42
Sulfur, %	0.21
NE _m [§] , Mcal/kg	2.19
NE _g [¶] , Mcal/kg	1.51

[†]Finisher diet was formulated to provide 315 mg/animal/d monensin (Rumensin; Elanco Animal Health), and depending on experimental treatment) 300 mg/animal/d Optaflexx (Elanco Animal health) fed during the final 28 dof (average across all pens) and removed 1 day prior to shipment or 36 mg/animal/d Experior (Elanco Animal Health) fed during the final 53 dof (average across all pens) and removed 4 days prior to shipment.

[‡]Feed additives were dispensed directly into the feed truck using Micro-Weigh Systems (Micro Beef Technologies, Amarillo, TX).

[§]NE_m = net energy for maintenance expressed as Mcal/kg

[¶]NE_g = net energy for gain expressed as Mcal/kg

Table 3.2. Results of mixed models analyses of cumulative health outcomes and mobility scores from steers that received lubabegron (EXP) or ractopamine hydrochloride (OPT)

Item	Treatment [†]		<i>P</i> -value
	EXP	OPT	
Total morbidity, % (SEM)			
Pulled once	2.45 (0.49)	2.74 (0.52)	0.68
Pulled twice	0.57 (0.23)	0.66 (0.25)	0.83
Pulled three times	0.57 (0.29)	0.41 (0.23)	0.57
Treatment category, % (SEM)			
Respiratory	1.61 (0.39)	1.80 (0.41)	0.79
Digestive	0.17 (0.13)	0.34 (0.20)	0.43
Musculoskeletal/trauma	0.70 (0.31)	0.63 (0.29)	0.84
Other	0.08 (0.08)	0.21 (0.16)	0.34
Mortality, % (SEM)			
Respiratory	0.47 (0.21)	0.28 (0.16)	0.61
Digestive [‡]	-	-	
Musculoskeletal/trauma [‡]	-	-	
Other	0.47 (0.21)	0.47 (0.21)	1.00
Total removals, % (SEM)	1.61 (0.39)	1.70 (0.40)	0.89
Veterinary medicine cost, \$/animal			
Processing	13.36 (0.17)	13.42 (0.17)	0.20
Treatment	0.67 (0.18)	0.87 (0.18)	0.42
Mobility Score [§] , % (n)			0.09
1, % (n)	95.39 (994)	97.31 (1011)	
2, % (n)	3.55 (37)	2.31 (24)	
3, % (n)	1.06 (11)	0.38 (4)	
4, % (n)	0 (0)	0 (0)	

[†]Treatments are: EXP = Exuperior delivered to target 36 mg/animal/d consumption; and OPT = Optaflexx delivered to target 300 mg/animal/d consumption.

[‡]Data were too sparse for analyses by appropriate statistical models

[§]Cattle mobility was scored by trained observer using a 4-point scale from the North American Meat Institute (NAMI, 2015) as animals exited trucks into the pen for antemortem inspection at the processing plant. Score 1 = Normal, walks easily, no apparent lameness, no change in gait; Score 2 = Exhibits minor stiffness, shortness of stride, slight limp, keeps up with normal cattle; Score 3 = Exhibits obvious stiffness, difficulty taking steps, obvious limp, obvious discomfort, lags behind normal cattle; Score 4 = Extremely reluctant to move even when encouraged by a handler, statue-like

Table 3.3. Model adjusted means and standard errors of the mean (SEM) for feedlot performance outcomes from steers that received lubabegron (EXP) or ractopamine hydrochloride (OPT)*

Item	Treatment [†]		SEM	P-value
	EXP	OPT		
Initial body weight, kg	373	374	5	0.70
<i>Dead and removed animals excluded[§]</i>				
Final body weight [‡] , kg	680	671	4	<0.01
Dry matter intake, kg/d	11.01	11.43	0.11	0.01
Average daily gain, kg/d	1.84	1.78	0.01	<0.01
Gain:feed	0.167	0.156	0.0018	<0.01
<i>Dead and removed animals included[#]</i>				
Final body weight [‡] , kg	671	665	4	0.06
Dry matter intake, kg/d	10.83	11.24	0.10	0.01
Average daily gain, kg/d	1.78	1.74	0.01	0.03
Gain:feed	0.165	0.155	0.0019	<0.01

*Trial was conducted as a randomized complete block design at 1 feedlot in Kansas, USA using steer blocks. A total of 2,081 steers were randomly allocated to one of two pens to form a block, and pens were randomly assigned to treatment (EXP or OPT)

[†]Treatments are: EXP = Experior delivered to target 36 mg/animal/d consumption; and OPT = Optaflexx delivered to target 300 mg/animal/d consumption.

[‡]A 4% shrink was applied to final body weight (i.e., body weight x 0.96).

[§]Performance outcomes calculated on the basis of all animals removed from the trial and mortalities excluded from the denominator

[#]Performance outcomes calculated on the basis where all animals enrolled in the trial are included in the denominator

Table 3.4. Model adjusted means and standard errors of the mean (SEM) for carcass characteristics from steers that received lubabegron (EXP) or ractopamine hydrochloride (OPT)*.

Item	Treatment†		SEM	P-value
	EXP	OPT		
Hot carcass weight, kg	442	431	2.6	<0.01
Dressed yield, %	64.87	64.15	0.15	<0.01
Longissimus muscle area, cm ²	95.74	91.23	0.71	<0.01
12th-rib fat thickness, cm	1.65	1.68	0.03	0.13
Marbling score‡	500	523	4.3	<0.01
Calculated yield grade	3.44	3.63	0.05	<0.01
USDA Yield Grade§, count (% of treatment group)				0.01
1	34 (3.27)	24 (2.31)		
2	264 (25.38)	199 (19.17)		
3	519 (49.90)	487 (46.92)		
4	194 (18.65)	293 (28.23)		
5	29 (2.79)	35 (3.37)		
USDA Quality Grade§, count (% of treatment group)				0.01
Prime	26 (2.50)	50 (4.82)		
Choice	856 (82.31)	882 (84.97)		
Select	142 (13.65)	96 (9.25)		
Sub-select	16 (1.54)	10 (0.96)		

*Trial was conducted as a randomized complete block design at 1 feedlot in Kansas, USA using steer blocks. A total of 2,081 steers were randomly allocated to one of two pens to form a block, and pens were randomly assigned to treatment (EXP or OPT)

†Treatments are: EXP = Exporior delivered to target 36 mg/animal/d consumption; and OPT = Optaflexx delivered to target 300 mg/animal/d consumption.

‡Scores ranging from 500 to 600 indicate a modest degree of marbling.

§P-value from multinomial (ordinal) regression testing the null hypothesis that the proportions of carcasses distributed across categories are equal between treatments; values are raw frequency statistics

Table 3.5. Model adjusted means, mean difference (MD), standard errors of the mean difference (SED), and standard errors of the mean (SEM) for economic outcomes from a partial budget assessment† of steers that received lubabegron (EXP) or ractopamine hydrochloride (OPT)*.

Item	Treatment		MD	SED	SEM	P-value
	EXP	OPT				
Purchase cost, \$/animal enrolled‡	1432.7	1435.2	-2.44	6.1	19.88	0.70
Feed and yardage cost, \$/animal enrolled§	811.59	842.45	-30.86	11.2	9.96	0.02
Cost of gain, \$/animal enrolled¶	1.25	1.33	-0.09	0.01	0.02	<0.001
Total cost, \$/animal enrolled	2303.2	2336.3	-33.15	12.1	20.91	0.02
Live sale basis revenue, \$/animal^	2366.9	2343.4	23.46	9.2	13.63	0.03
Dressed sale basis revenue, \$/carcass⦿	2339.6	2308.8	30.76	9.22	12.04	<0.01
Net Return - live basis, \$/animal^	63.7	7.1	56.61	9.37	12.94	<0.001
Net Return - dressed basis, \$/carcass^	31.4	-29.3	60.67	12.6	13.70	<0.001

*Trial was conducted as a randomized complete block design at 1 feedlot in Kansas, USA using steer blocks. A total of 2,081 steers were randomly allocated to one of two pens to form a block, and pens were randomly assigned to treatment (EXP or OPT)

† The partial budget used cattle market prices reflective of the time the trial occurred, August 2022 through February 2023.

‡ Feeder steer price = \$172.24 /cwt

§Price includes dry feed, feed markup, and yardage from the central plains; \$406.95/ton

¶Live fed price for steers = \$157.77

^ Weekly negotiated steer price, live free-on-board, over 80% Choice, from USDA-AMS report (LM_CT150) 5 area weekly weighted average direct slaughter cattle

⦿ Weekly negotiated steer price, dressed delivered, over 80% Choice, from USDA-AMS report (LM_CT150) 5 area weekly weighted average direct slaughter cattle; used as dressed base price that carcass-based premiums and discounts were then applied to. Weekly premiums and discounts that were applied to actual pen-level carcass weights from each category after accounting for the dressed base price, from USDA-AMS report (LM_CT169) 5 area weekly slaughter cattle -- premiums and discounts

^ Net return = total pen revenue --total pen costs; then divided by the number of cattle shipped or carcasses graded.

Table 3.6. Model adjusted means and standard errors of the mean (SEM) for calculated estimates of carbon dioxide equivalent (CO₂e) emissions from the production of steers that received lubabegron (EXP) or ractopamine hydrochloride (OPT)*.

Item	EXP	OPT	SEM	P-value
Pre-feedlot calf footprint [†]				
Per animal enrolled	6541.1	6545.6	32.12	0.66
Feedlot finishing footprint [‡] , kg CO ₂ e				
Feedlot operations [§] , per animal enrolled	921.7	954.8	10.62	0.03
Manure [¶] , per animal enrolled	396.7	414.7	4.84	0.01
Enteric methane [^] , kg of CO ₂ e per animal enrolled	488.5	506.7	5.71	0.02
Total finishing [‡] , animal enrolled	1806.9	1876.2	21.09	0.02
Total finishing [‡] , per kg final BW	2.69	2.82	0.03	<0.01
Total finishing [‡] , per kg HCW	4.08	4.35	0.06	<0.01
Total footprint [‡] , kg CO ₂ e				
Per animal enrolled	8348.0	8421.8	31.07	<0.01
Per kg final BW	12.49	12.76	0.048	<0.01
Per kg HCW	19.26	19.89	0.089	<0.01

*Trial was conducted as a randomized complete block design at 1 feedlot in Kansas, USA using steer blocks. A total of 2,081 steers were randomly allocated to one of two pens to form a block, and pens were randomly assigned to treatment (EXP or OPT)

[†]Calculated estimate of the total CO₂e generated from each calf (from cow-calf production until feedlot purchase) based on incoming animal weight and breed.

[‡]Calculated estimates of CO₂e generated during the finishing phase (trial period).

[§]Calculated estimates of CO₂e generated from the production of dry feed ingredients, commodity trucking, and fuel and utilities at the feedlot

[¶]Calculated estimates of the total CO₂e associated with manure, which includes: manure methane, direct manure N₂O, indirect manure N₂O from volatilization, and indirect manure N₂O from leaching and runoff

[^]Calculated estimates of CO₂e enteric methane produced by the animal

[‡]Sum of estimated CO₂e generated during the finishing period from feedlot operations, manure, and enteric methane

[‡]Total calculated estimates of CO₂e from the pre-feedlot calf footprint and finishing period footprint

Appendix

Appendix Table 3.A. Descriptive statistics of revenue and cost parameters that were used in a partial budget

Parameter	Value	Source
Revenue		
Live harvest price [†] , \$/45.4 kg	157.77	LM_CT150 (USDA-AMS)
Dressed harvest price [‡] , \$/45.4 kg	251.10	LM_CT150 (USDA-AMS)
Quality grade premium/discount [§] , \$/45.4 kg		LM_CT169 (USDA-AMS)
Prime	24.20	
Choice	0.00	
Select	-22.60	
Standard	-34.60	
Yield grade premium/discount [§] , \$/45.4 kg		LM_CT169 (USDA-AMS)
1	5.10	
2	2.10	
3	0.00	
4	-10.10	
5	-13.80	
Carcass weight discount [§] , \$/45.4 kg		LM_CT169 (USDA-AMS)
Less than 249 kg	-30.80	
Greater than 476 kg	-16.70	
Dressed cull price [¶] , \$/45.4 kg	153.99	LM_CT168 (USDA-AMS), (Horton et al., 2021)
Costs		
Feeder purchase price [^] , \$/45.4 kg	174.24	Oklahoma City auctions (LMIC)
Feed and yardage [!] , \$/907 kg	406.95	Central plains rations (CattleFax)
Processing cost [‡] , \$/animal	18.8 2	Estimated (PBS Animal Health)
Morbidity cost, \$/treatment	23.60	(USDA-NAHMS, 2013)
Mortality cost [^] , \$/death	38.24	(Sparks Comp. Inc., 2002), (U.S. BLS)

[†] Weekly negotiated steer price, live free-on-board, over 80% Choice, from USDA-AMS report (LM_CT150) 5 area weekly weighted average direct slaughter cattle.

[‡] Weekly negotiated steer price, dressed delivered, over 80% Choice, from USDA-AMS report (LM_CT150) 5 area weekly weighted average direct slaughter cattle; used as dressed base price that carcass-based premiums and discounts were then applied to.

[§] Weekly premiums and discounts that were applied to actual pen-level carcass weights from each category after accounting for the dressed base price, from USDA-AMS report (LM_CT169) 5 area weekly slaughter cattle – premiums and discounts.

[¶] Price that was applied to weights of animals removed from the trial [actual live weight converted to estimated carcass weight (Tatum et al., 2012)], which was from weekly dressed Breaker cow prices (over 227 kg) from USDA-AMS report (LM_CT168) national weekly

direct cow and bull report – negotiated price, for which only a percentage of the price was used as categorized by mean pen-level carcass weight of removed animals (Horton et al., 2021).

[^] Weekly price for medium and large frame #1 feeder steers Oklahoma City auctions that was applied to initial pen weight of trial animals, based on a weighted average price of 364 and 409 kg pricing categories

^{||} Monthly feed costs that were applied to the total amount of dry feed consumed per pen based on the price during their placement month; the price accounts for feed, feed markup, and yardage.

[⌘] Based off a constructed processing protocol using a typical product regimen with prices sourced from PBS Animal Health

[♠] Inflation adjusted from reported 2002 render fee of 24.11 \$/dead animal (Sparks Comp. Inc., 2002) to the mean 2015 to 2021 producer price index value for animal slaughtering and processing (U.S. BLS).

Chapter 4 - A randomized trial comparing the effectiveness of tulathromycin, tulathromycin + ketoprofen, and tildipirosin for treatment of naturally occurring bovine respiratory disease in feedlot cattle that did not receive metaphylaxis

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Abstract

Our objective was to compare the relative effectiveness of three macrolide antimicrobials for the initial treatment of bovine respiratory disease (BRD) in medium-risk feedlot steers and heifers that did not receive metaphylaxis. Steers and heifers ($n = 704$; 734 ± 111 lb [333 ± 50 kg]) were enrolled at a commercial Kansas feedlot. Animals were eligible for inclusion if they exhibited clinical signs of BRD from natural exposure and had not previously received any antimicrobial treatment for BRD, including metaphylaxis. At the time of first BRD diagnosis, individual animals were randomly allocated to be administered treatment with either tulathromycin, tulathromycin + ketoprofen, or tildipirosin. General and generalized linear mixed models, accounting for time and lot, were used for statistical analyses. At enrollment, initial body weight ($P = 0.40$), rectal temperature ($P = 0.50$), and days on feed ($P = 0.24$) did not differ significantly

between treatments. There was no evidence of differences in any morbidity outcome during the first 60 days after enrollment, the first 100 days after enrollment, or through closeout ($P \geq 0.14$). Likewise, there was no evidence of differences in any mortality outcome across these same evaluation periods ($P \geq 0.41$). Treatment success, defined as animals that were not retreated and did not die, ranged from 74.46% to 75.45% through closeout ($P = 0.96$). In medium-risk feedlot cattle managed without on-arrival metaphylaxis, no differences in morbidity or mortality outcomes were observed among the three macrolide treatments - tulathromycin, tulathromycin + ketoprofen, or tildipirosin.

Keywords: Macrolide, Arovyn, Draxxin KP, Zuprevo

Introduction

Bovine respiratory disease (BRD) remains a significant health challenge in the beef industry, affecting an estimated 16.2% of feedlot cattle and accounting for the majority of injectable antimicrobial use in North America.^{1,2,3} Bovine respiratory disease is well established as the leading cause of morbidity and mortality in feedlot systems, contributing to substantial economic losses.^{4,5}

Macrolide antimicrobials are widely regarded as effective options for treatment of BRD.⁶ Tildipirosin (TIL^a), tulathromycin (TUL^b), and tulathromycin + ketoprofen (TUL+K^c) are all macrolides approved for BRD therapy. Despite their common use, few head-to-head trials published in the peer-reviewed literature in commercial feedlot settings have compared the first-treatment effectiveness of TIL, TUL, and TUL+K for naturally occurring clinical BRD. In this study, TUL was Arovyn, approved by the FDA in 2021⁷ following expiration of the Draxxin^d patent.

The introduction of TUL+K in the United States has generated particular interest because it combines tulathromycin with the non-steroidal anti-inflammatory drug (NSAID) ketoprofen.

NSAID inclusion may reduce fever and inflammation, potentially improving clinical outcomes and animal welfare; however, consistent evidence for enhanced treatment success or performance is lacking.⁸ While TUL+K contains this additional anti-inflammatory component, TUL and TIL also differ structurally, with TUL classified as a 15-membered ring macrolide and TIL as a 16-membered ring macrolide.^{9,10}

Existing literature comparing macrolides with and without NSAID inclusion for BRD treatment is limited, and prior studies have often reported few differences in treatment outcomes among TIL, TUL, and/or TUL+K.^{11,12} However, since differences in first-treatment success, morbidity, or mortality could be clinically and economically important, evaluating these regimens under commercial conditions is critical to inform evidence-based treatment protocols, optimize animal welfare, and guide judicious antimicrobial use.

Treatment responses can differ depending on cattle health status, making it important to consider the risk level of the study population. Feedlot cattle are commonly categorized as low-, medium-, or high-risk for developing BRD, with some operations also describing an ultra-high-risk category; however, these classifications are not standardized and rely on factors such as age, weaning status, weight, weather, transport distance, commingling, and health history.^{13,14,15,16,17,18} Much of the existing research on BRD, including treatment-effectiveness studies, has focused on high-risk cattle, while medium-risk populations have been evaluated far less frequently and remain inconsistently defined in the literature.^{19,20}

The primary objective of this study was to evaluate the relative effectiveness of administering TUL, TUL+K, or TIL, for the initial treatment of BRD in medium-risk feedlot steers and heifers, that did not receive metaphylaxis, with subsequent health outcomes assessed at 60- and 100-days post-enrollment as well as at the end of the feeding period (closeout).

Materials and Methods

All study procedures were reviewed and approved by Kansas State University's Institutional Animal Care and Use Committee (IACUC; Approval number IACUC-4785).

Cattle population

A total of 704 mixed beef-breed steers and heifers classified as medium risk upon arrival were sourced from a population of 11,464 candidate animals across 85 single-pen lots (pen size range: 52 to 170 head) beginning in October 2023 through August 2025. Cattle were housed at a commercial feedlot in Kansas. Medium risk status was defined according to the feedlot's standard operational classification, which was based on an expected average lot-level BRD morbidity of approximately 12%.

Cattle were enrolled at the time of first clinical BRD diagnosis and randomly allocated to one of three treatment groups: TUL, TUL+K, and TIL. The primary health related outcome evaluated was first treatment success

Treatment structure and experimental design

This study was conducted with a one-way factorial treatment structure in a completely randomized design. Individual cattle were eligible for inclusion if they required a first-time treatment for clinical BRD and met the following criteria: (1) absence of abnormal clinical signs referable to organ systems other than the respiratory tract, (2) no prior treatment for BRD, (3) a rectal temperature $\geq 103.5^{\circ}\text{F}$ ($\geq 39.7^{\circ}\text{C}$), and (4) between 1 and 60 days-on-feed (DOF). All animals were monitored under commercial feedlot conditions. Cattle were randomly assigned to treatment groups using a computer-generated allocation table provided to the hospital lead but not those monitoring cattle health in the pens. All antimicrobials were administered using 16-gauge $\times$ 5/8-inch (15.88 mm) needles, in accordance with manufacturer recommendations and

Beef Quality Assurance guidelines. To ensure accurate dosing, each animal was individually weighed at allocation. Study animals were monitored through closeout.

An a priori sample size calculation using $\alpha = 0.05$ and $\beta = 0.20$ (80% power) estimated that 250 animals per treatment group would be required to detect an absolute difference in first treatment success of 4.17%, using a likelihood ratio test for two independent proportions in EpiTools^e and an expected first treatment success of $81.72\% \pm 2.76\%$ in low- to medium-risk cattle treated with tildipirosin.²¹

Cattle in the TUL group received a single subcutaneous (SC) injection of TUL at a dosage of 1.1 mL/100 lb body weight (BW; 2.5 mg TUL per kg BW). Cattle in the TUL+K group received a single subcutaneous (SC) injection of TUL+K at a dosage of 1.1 mL/100 lb body weight (2.5 mg TUL and 3 mg ketoprofen per kg BW). Cattle in the TIL group received a single SC injection of TIL at a dosage of 1 mL/100 lb (4 mg /kg) BW. Post-treatment intervals were 5 days after the first BRD treatment and 3 days after the second and third treatments (Table 1), reflecting the standard treatment protocol used at the study feedlot.

Cattle management and stewardship

Upon arrival, cattle were processed following standard commercial feedlot protocols for health and production management. All steers received an ear tag with a lot number unique to each pen, an ear tag with a number unique to each animal, a 5-way viral vaccine^f administered subcutaneously (SC), a SC injection of an internal parasiticide^g, a foot rot autogenous vaccine^h, an oral anthelminticⁱ, and an implant administered SC in the ear containing 100 mg trenbolone acetate and 14 mg estradiol benzoate^j. Heifers received similar processing with the addition of a pregnancy check; those determined to be bred were administered a prostaglandin analog^k, a

corticosteroid^l and oxytetracycline^m. Selected lots of cattle (both steers and heifers) were administered a pour-on insecticideⁿ and foot bath^o.

Cattle were housed in open-air, dirt-floored pens constructed of steel pipe and arranged along central feed alleys. Each pen was equipped with an automatic water fountain providing ad libitum access to fresh well water. Animals were processed through a handling system equipped with an individual animal scale and a chute-side computer for data collection and management.

Cattle had ad libitum access to water and standard, mixed complete feedlot diets formulated to meet or exceed the nutritional requirements for beef cattle.²² Diets were prepared using truck-mounted mixer boxes equipped with electronic load cells and were delivered to pens up to three times daily. Animals were transitioned to a high-concentrate finishing diet through a series of step-up rations. Diet formulations and transitions followed commercial feedlot protocols and were standardized across all experimental groups.

Primary health outcomes were evaluated at three time points: 60 days post-enrollment, 100 days post-enrollment, and over the full duration of the feeding period through closeout. Outcomes included BRD retreatment risk, first-treatment failure, second and third retreatments, chronicity, railers, wastage, total removals, total mortality, BRD-specific mortality, other-cause mortality, and DOF from enrollment to death (total and BRD-related), as defined in Table 2. For each outcome, values were calculated separately within each evaluation window. BRD retreatment risk was defined as the proportion of enrolled animals that required a second BRD treatment within the specified time horizon. First-treatment failure was assessed using two definitions, each evaluated at 60 days, 100 days, and closeout: (1) the percentage of enrolled animals that either required a second BRD treatment or died from any cause within the evaluation period, and (2) the percentage of enrolled animals that either required a second BRD

treatment or died specifically due to BRD within the evaluation period. First-treatment success, which is the inverse of the first-treatment failure definition, was defined as the percentage of enrolled animals that did not require a second BRD treatment and did not die from any cause during the evaluation period.

Second and third retreatments were defined as the proportion of enrolled animals that required additional BRD treatments (i.e., a third or fourth treatment) within the specified evaluation period (60 days, 100 days, or through closeout). Chronicity was defined as the percentage of enrolled animals classified as chronic cases by the end of each evaluation window, and wastage was defined as the proportion of chronic animals that did not die within that same period. Mortality outcomes were categorized as total mortality (death from any cause), BRD-specific mortality, and mortality due to other causes, all calculated separately for each evaluation period. Days on feed from enrollment to death was recorded separately for total mortality and BRD-related mortality within each evaluation period.

Cattle were observed daily by trained animal health personnel who were masked to treatment group status and who determined the need for retreatment based on clinical signs of illness. Animals were eligible for retreatment if clinical signs persisted beyond the post-treatment interval. While rectal temperature was recorded at the time of evaluation, it was not used as a decision criterion for retreatment. Body weight and DOF were documented at each retreatment event. Lots were eligible for inclusion if the average arrival weight was between 550 and 800 lb, and no metaphylaxis or other group-level antimicrobial treatments were administered.

The retreatment protocol for BRD retreatment (second overall treatment) consisted of SC injection of florfenicol^P at 6.0 mL/100 lb BW. Second-time BRD retreatment (third and final overall treatment) involved a SC injection of danofloxacin^Q at 1.5 mL/100 lb BW. Cattle

requiring a second BRD retreatment (third overall BRD treatment) were classified as chronic. All non-BRD diseases were treated in accordance with standard feedlot protocols developed by the consulting veterinarian(s). Protocols for managing non-BRD illnesses were applied consistently across all experimental groups. Necropsies were performed according to standard feedlot protocol by trained feedlot personnel or a licensed veterinarian, and a cause of death was recorded for all mortalities. Health evaluations were carried out by animal caretakers who remained blinded to treatment assignments throughout the study.

Statistical analyses

General and generalized linear mixed models (LMM and GLMM, respectively; Proc GLIMMIX SAS 9.4^r;) were fit to evaluate treatment effects on response variables of interest. The fixed effect was treatment (TUL, TUL+K, TIL) while lot nested within year was included as a random intercept. In all models, the individual steer or heifer was specified as both the experimental and observational unit. Continuous outcomes were analyzed using LMM (Proc GLIMMIX) with an identity link and gaussian distribution. Model parameters were estimated using restricted maximum likelihood with a Newton-Raphson optimization algorithm incorporating ridging. The Kenward-Roger method was used to adjust degrees of freedom for standard error estimation. Assumptions of homoscedasticity and normality were evaluated through visual inspection of marginal studentized residual plots. Dichotomous outcomes were analyzed using GLMM (Proc GLIMMIX) with a logit link and binary distribution, with the same model inputs, and again included a Kenward-Roger degrees of freedom adjustment and Newton-Raphson with ridging optimization procedures. All GLMM estimates were back-transformed to their original scale for interpretation. A significance level of $\alpha = 0.05$ was established a priori for all models, and multiple pairwise comparisons among treatment means were adjusted using the

Tukey-Kramer method. Survival analysis was conducted to compare time-to-mortality among treatment groups. Time zero was defined as the day each animal received its assigned BRD treatment. Calves that remained alive at the end of the study or were removed for reasons unrelated to mortality were treated as right-censored observations. Kaplan–Meier survival functions were estimated for each treatment group, and differences among groups were evaluated using the log-rank test. For visualization, survival curves were truncated at 100 days after treatment allocation to provide a consistent display window across groups (figure 1); however, statistical analyses were performed using the full follow-up period.

Results

Cattle were allocated at an average of 13 DOF (range: 0 to 60 DOF) between October 23, 2023, and March 20, 2025. Table 3 summarizes the enrollment characteristics of steers and heifers included in the trial, where 232, 237, and 235 were enrolled for TUL, TUL+K, and TIL, respectively, for a total of 704 cattle, fewer than the 750 animals targeted by the a priori sample size calculation. Minor differences in group size reflected normal variation in enrollment under commercial conditions. Of the enrolled cattle, 72.8% were heifers and 27.2% were steers. Enrollment occurred throughout the study period and was concentrated in the fall arrival months, with approximately two-thirds of cattle originating from September through November 2024 lots. The average individual animal weight at allocation was 734 lb. (range 450 to 1400 lb). There were no significant differences among treatment groups in enrollment body weight ($P = 0.40$), rectal temperature ($P = 0.50$), or DOF ($P = 0.24$).

Health results at 60 d post enrollment

Health outcomes assessed through 60 days after enrollment are presented in Table 4. Retreatment risks (treated twice) for TUL, TUL+K, and TIL were 20.9%, 23.9%, and 21.6%,

respectively, and did not differ significantly among treatment groups ($P = 0.73$). First-treatment success also did not differ among groups, with model-adjusted estimates of 74.4%, 74.0%, and 72.9% for TUL, TUL+K, and TIL, respectively ($P = 0.94$). Similarly, no treatment-related differences were detected for the probability of first treatment failure and/or any death ($P = 0.94$) or first treatment failure and/or BRD-attributed death ($P = 0.96$). The probability of a second ($P = 0.72$) or third ($P = 0.53$) BRD retreatment also did not differ significantly among groups.

There were no significant differences among treatments for the proportion of cattle classified as chronic ($P = 0.44$), railed ($P = 0.22$), wastage ($P = 0.66$), or total removals ($P = 0.30$). BRD-specific mortality for TUL, TUL+K, and TIL was 5.3%, 5.6%, and 4.0%, respectively ($P = 0.70$). Total mortality ($P = 0.97$) and miscellaneous mortality ($P = 0.41$) did not differ among treatments. Mean DOF from enrollment to BRD death ($P = 0.10$) and from enrollment to any death ($P = 0.11$) also did not differ significantly among groups.

Health results at 100 d post enrollment

Treatment effects evaluated through 100 days after enrollment are shown in Table 5. Retreatment risks (treated twice) were 23.5% for TUL, 25.0% for TUL+K, and 23.0% for TIL, with no evidence of a treatment effect ($P = 0.86$). First-treatment success also did not differ among groups, with model-adjusted estimates of 70.9%, 72.4%, and 71.7% for TUL, TUL+K, and TIL, respectively ($P = 0.94$). The probability of experiencing a first treatment failure and/or any death ($P = 0.94$) or BRD-related death ($P = 0.98$), as well as second ($P = 0.92$) and third ($P = 0.14$) BRD retreatments did not differ significantly among treatment groups.

The proportions of cattle categorized as chronic ($P = 0.18$), railed ($P = 0.65$), wastage ($P = 0.55$), or removed for any reason ($P = 0.31$) also did not differ significantly among treatment groups. BRD-specific mortality for TUL, TUL+K, and TIL was 6.6%, 6.2%, and 4.5%,

respectively ($P = 0.57$), and no treatment differences were detected for total ($P = 0.97$) or miscellaneous ($P = 0.47$) mortality. Mean DOF to BRD death ($P = 0.21$) and to any death ($P = 0.09$) likewise did not differ significantly.

Health results at closeout

The effects of experimental treatments on health outcomes through closeout are in Table 6. Retreatment risks (treated twice) for TUL, TUL+K, and TIL were 23.5%, 25.4% and 22.9%, respectively, which did not differ significantly ($P = 0.81$). First-treatment success also did not differ among groups, with model-adjusted estimates of 70.5%, 71.7%, and 71.9% for TUL, TUL+K, and TIL, respectively ($P = 0.94$). There was no evidence for a difference among treatment groups for the probability of having a first treatment failure and/or any death ($P = 0.94$), or BRD death ($P = 0.59$). There was no evidence of a difference among treatment groups for the probability of having a second BRD retreatment ($P = 0.93$) or third BRD retreatment ($P = 0.20$). There were no significant differences for the probability of cattle classified as chronic ($P = 0.25$), railed ($P = 0.78$), wastage ($P = 0.64$), or total removals ($P = 0.31$).

BRD-specific mortality for TUL, TUL+K, and TIL were 7.1%, 6.2%, and 4.5%, respectively, which did not differ significantly ($P = 0.48$). There was no evidence of a difference among treatment groups for total ($P = 0.64$) or miscellaneous ($P = 0.73$) mortality. There was no evidence of differences among treatment groups for the mean DOF from enrollment to BRD death ($P = 0.10$) or from enrollment to any death ($P = 0.11$). The survival analysis also indicated no difference among treatments (Figure 1; $P = 0.66$).

Discussion

This study evaluated the effectiveness of first BRD treatments in medium-risk cattle, a population where lot-level BRD morbidity averages approximately 12% in the absence of

metaphylaxis at arrival; observed BRD mortality in the enrolled cattle was approximately 6% through closeout. Macrolides, particularly tulathromycin, are frequently regarded as among the most effective antimicrobial options for BRD treatment, with meta-analyses consistently ranking them as top-performing therapies.²³ Overall, this study demonstrated no evidence for differences in health outcomes for the macrolide therapies used for first BRD treatment in this study population.

Medium-risk feedlot cattle are less clearly defined than low- or high-risk groups, and outcomes within this category often exhibit greater variability. This pattern was evident in the present study. Medium-risk status was defined based on an expected lot-level BRD morbidity of approximately 12%, yet the observed average morbidity was 6.2%, with lot-level first-treatment risk ranging from 0% to 26.5%. Similar variability has been described in other studies evaluating medium-risk cattle that did not receive metaphylaxis.^{20,24} Interpretation of these findings should therefore be considered in context of the study population. Medium-risk cattle are evaluated far less frequently than high-risk cattle in BRD treatment effectiveness trials, and definitions of medium risk are not standardized across studies. Given these inconsistencies and the variability in BRD outcomes observed here and elsewhere, treatment effects reported in high-risk cattle may not be directly comparable to those in medium-risk groups. The present study contributes needed evidence on macrolide performance specifically in medium-risk cattle managed without metaphylaxis, a population for which published data remains relatively sparse.

There is limited published literature directly comparing the efficacy of macrolide antimicrobials with and without NSAID inclusion; however, previous research found no evidence for differences in treatment outcomes with TUL+K compared to TIL in high-risk cattle that received tulathromycin metaphylaxis.¹¹ Consistent with the results described here, several

studies have reported comparable treatment responses between TUL and TIL,^{21,25} although a different study²⁶ observed reduced mortality and improved first-treatment success in heifers administered TUL compared to TIL (notably, tulathromycin in these studies did not contain ketoprofen).

Other comparative work has likewise demonstrated few differences between macrolide-based regimens. In low- to medium-risk cattle, no differences were observed between TUL and TIL in first-treatment success or BRD case fatality risk.²⁷ Similarly, in steers and heifers at medium BRD risk, treatment outcomes did not differ between these products.²⁸ Comparisons of TUL+K and TUL for BRD treatment also failed to demonstrate a clear advantage of adding ketoprofen.^{12,29}

Together, these prior findings are consistent with the results of the present study, in which no significant differences in morbidity or mortality outcomes were observed among TUL+K, TUL, and TIL for the treatment of naturally occurring BRD. Survival curves further demonstrated that survival remained similar across treatment groups throughout the feeding period, with no evidence of separation at early or late time points. This time-to-event perspective complements endpoint mortality analyses and reinforces the conclusion that treatment choice did not meaningfully alter survival dynamics. Cause of death was assigned according to standard feedlot diagnostic procedures; however, complete postmortem examination may not have been performed for all mortalities under commercial conditions, which could result in some degree of misclassification of BRD mortality. However, because the sample size was smaller than anticipated, reducing the statistical power to detect treatment effects, and the magnitude of potential treatment effect may be quite small, these findings should be interpreted with caution and should not be taken as evidence that treatment effects are absent. Differences smaller than

the 4.17% detectable effect used for sample size estimation may still be biologically, economically, and operationally important from animal health, welfare, and feedlot management perspectives. The timing of retreatment following initial therapy is an important consideration in BRD treatment studies. In the present study, the post-treatment interval reflected the standardized commercial protocol and was applied consistently across all treatment groups to maintain a similar time at risk for subsequent health outcomes. As cattle became eligible for retreatment after a fixed interval, administration of subsequent therapy may influence the apparent effectiveness of the initial antimicrobial. Evaluation of alternative post-treatment intervals was beyond the scope of this study.

We additionally evaluated outcomes at 60 and 100 days on feed (DOF), as these intervals are commonly used as intermediate endpoints in commercial feedlot trials.^{30,11} Analyses at these timepoints produced results consistent with those from the full closeout period, with no significant differences detected among treatment groups. Across the three evaluation periods (60 days post-enrollment, 100 days post-enrollment, and through closeout), health outcomes did not differ significantly among calves treated with TUL, TUL+K, or TIL for first treatment of BRD. Retreatment risks, treatment failures, chronic classifications, removal categories, and BRD-specific or all-cause mortality did not differ statistically among treatment groups across any follow-up period, indicating that no detectable differences emerged within the timeframes evaluated.

Conclusions

In medium-risk feedlot cattle managed without on-arrival metaphylaxis, there was no evidence for differences in morbidity and mortality outcomes among TUL, TUL+K, and TIL when used as first-line BRD treatments, indicating that selection among these three

antimicrobials may have limited influence on health outcomes under these conditions. These findings also emphasize that treatment responses can vary across cattle populations with different BRD risk levels,¹¹ reinforcing the need to interpret treatment performance within the context of the specific cattle population. Future work should expand on these results by evaluating the economic and operational impacts of different antimicrobial choices, as well as how treatment strategies can be refined across varying cattle types, management systems, and disease pressures. Continued evaluation of these factors will be essential to optimizing BRD therapeutic approaches across diverse study populations and production environments.

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Conflicts of interest

One of the co-authors is employed by Merck Animal Health which provided funding for this study. Other co-authors have received grant funding and/or consulting revenue from both Merck and Zoetis.

Author contributions

All authors were involved in the conception and design of the study. All authors were involved in acquisition of study data. TM and DR were involved in analysis and interpretation of study data. TM and DR were involved in the manuscript drafting and/or revising process. All authors have approved the final version of this manuscript for publication.

Endnotes

- ^aTIL; Zuprevo[®], Merck Animal Health, Madison, NJ
- ^bTUL; Arolyn[®], Merck Animal Health, Madison, NJ
- ^cTUL+K; Draxxin KP[®], Zoetis Animal Health, Parsippany, NJ
- ^dDraxxin[®], Zoetis Animal Health, Parsippany, NJ
- ^eBovi-Shield Gold[®] IBR-BVD , Zoetis Animal Health, Parsippany, NJ
- ^fBovi-Shield Gold[®] IBR-BVD , Zoetis Animal Health, Parsippany, NJ
- ^gDectomax[®] Injectable, Zoetis Animal Health, Parsippany, NJ
- ^hAutogenous Vaccine, Vaxxinova, Worthington, MN
- ⁱSafe-Guard[®] Suspending 10%, Merck Animal Health, Madison, NJ
- ^jSynovex[®] Choice, Zoetis Animal Health, Parsippany, NJ
- ^kLutalyse[®] HighCon; Zoetis Animal Health, Parsippany, NJ
- ^lDexamethasone; VetOne, Boise, ID
- ^mVetrimycin[®] 200; VetOne, Boise, ID
- ⁿClean-Up[®] II; Elanco Animal Health, Greenfield, IN
- ^oHealMax[®] Foot Bath; AgroChem, Inc., Saratoga Springs, NY
- ^pNuflor[®]; Merck Animal Health, Madison, NJ
- ^qAdvocin[®]; Zoetis Animal Health, Parsippany, NJ
- ^rSAS Institute Inc., Cary, NC

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Tables and Figures

Table 4.1. Characteristics of antimicrobial treatments, tulathromycin (TUL), tulathromycin and ketoprofen (TUL+K), and tildipirosin (TIL) used as first treatment for clinical bovine respiratory disease in beef cattle in a randomized clinical trial conducted at a commercial feedlot.

Item	Treatment		
	TUL [†]	TUL+K [‡]	TIL [§]
Dosage, mL/100 lb	1.1	1.1	1
Post-treatment-interval , days	5	5	5
Pre-harvest withdrawal [¶] , days	18	18	21

[†]Tulathromycin (Arovyn[®]; Merck Animal Health, Madison, NJ) administered subcutaneously.

[‡]Tulathromycin and ketoprofen (Draxxin KP[®]; Zoetis Animal Health, Parsippany, NJ) administered subcutaneously.

[§]Tildipirosin (Zuprevo[®]; Merck Animal Health, De Soto, KS) administered subcutaneously.

^{||}The interval between antimicrobial administration and the earliest point at which an animal could be re-treated if clinical signs of BRD persisted or reappeared.

[¶]Time between when the antimicrobial was administered and when the animal could be harvested for consumption.

Table 4.2. Definitions and calculations of individual animal-level health outcome variables in a randomized clinical trial which evaluated feedlot cattle treated with either tulathromycin (TUL), tulathromycin and ketoprofen (TUL+K), and tildipirosin (TIL) upon first clinical signs of BRD.

<i>Morbidity</i>		
Retreatment Risk (treated twice)	% of enrolled animals treated for BRD a second time	Number treated for BRD2 / number enrolled
First Treatment Success	% of enrolled animals not treated for BRD a second time and did not die of any cause	Number not treated for BRD2 and did not die / number enrolled
First Treatment Failure, Retreatment and/or any death	% of enrolled animals treated for BRD a second time and/or died of any cause	Number treated for BRD2 and/or died of any causes / number enrolled
First Treatment Failure, Retreatment and/or BRD death	% of enrolled animals treated for BRD a second time and/or died of BRD	Number treated for BRD2 and/or died of BRD / number enrolled
Second Retreatment	% of BRD2 animals treated for BRD a third time	Number treated for BRD3 / number treated for BRD2
Third Retreatment	% of BRD3 animals treated for BRD a fourth time	Number treated for BRD4 / number treated for BRD3
Chronicity	% of enrolled animals that became chronic	Number of chronic animals / number enrolled
Wastage	% of enrolled animals that became chronic that did not die	Number of wastage animals / number enrolled
Railer	% of enrolled animals that were railed	Number of railed animals/ number enrolled
Total removals	% of enrolled animals that became chronic, were railed, or died	Number of total removals/number enrolled
<i>Mortality</i>		
Total mortality	% of enrolled animals that died of all causes	Number of enrolled animals that died of all causes/ number enrolled
BRD mortality	% of enrolled animals that died of BRD	Number of enrolled animals that died of BRD / number enrolled
Other mortality	% of enrolled animals that died of miscellaneous causes	Number of enrolled animals that died of miscellaneous causes / number enrolled

Table 4.3. Model adjusted means and standard errors of the means (SEM) for enrollment data on feedlot cattle randomly assigned tulathromycin (TUL), tulathromycin and ketoprofen (TUL+K), or tildipirosin (TIL) treatments upon first clinical signs of BRD.*

Item	Treatment			SEM	<i>P</i> -value
	TUL [†]	TUL+K [‡]	TIL [§]		
Animals enrolled, <i>n</i>	232	237	235	-	-
Initial body weight, lb	742.12	739.13	750.25	10.9	0.40
Days on feed at enrollment, <i>n</i>	13.54	14.89	15.24	1.27	0.24
Rectal temperature at enrollment, °F	104.43	104.36	104.34	0.08	0.50

*A randomized clinical trial at a commercial feedlot in Kansas; animals randomly assigned to one of the 3 experimental treatments (macrolide antibiotics).

[†]Tulathromycin (Arovyn[®]; Merck Animal Health, Madison, NJ) administered subcutaneously.

[‡]Tulathromycin and ketoprofen (Draxxin KP[®]; Zoetis Animal Health, Parsippany, NJ) administered subcutaneously.

[§]Tildipirosin (Zuprevo[®]; Merck Animal Health, De Soto, KS) administered subcutaneously.

Table 4.4. Model-adjusted means and SEM for health outcomes observed during the first 60 days following treatment of feedlot cattle with tulathromycin (TUL), tulathromycin and ketoprofen (TUL+K), or tildipirosin (TIL) at first clinical signs of BRD first 60 d after enrollment.*

Table 4. Model-adjusted means and SEM for health outcomes observed during the first 60 days following treatment of feedlot cattle with tulathromycin (TUL), tulathromycin and ketoprofen (TUL+K), or tildipirosin (TIL) at first clinical signs of BRD first 60 d after enrollment.*										
Items,	Treatment									P-value
	TUL [†]			TUL+K [‡]			TIL [§]			
	Mean	95% CI	n	Mean	95% CI	n	Mean	95% CI	n	
Morbidity, %										
Retreatment Risk (treated twice) ¹	20.91	15.19 – 28.07	57	23.85	17.69 – 31.33	64	21.61	15.77 – 28.89	60	0.73
First Treatment Success,										
No retreatment and no death	74.37	66.95 – 80.60	166	73.98	66.60 – 80.21	170	72.92	65.34 – 79.37	165	0.94
No retreatment and no BRD death	75.45	68.06 – 81.59	168	74.53	67.11 – 80.75	171	74.46	66.93 – 80.76	168	0.96
First Treatment Failure,										
Retreatment and/or any death	25.63	19.40 – 33.05	66	26.02	19.79 – 33.40	67	27.08	20.63 – 34.66	70	0.94
Retreatment and/or BRD death	24.55	18.41 – 31.94	64	25.47	19.25 – 32.89	66	25.54	19.24 – 33.07	67	0.96
Second Retreatment [¶]	57.37	41.98 – 71.46	34	50.05	35.59 – 64.55	33	51.01	35.93 – 65.90	30	0.72
Third Retreatment	34.65	20.09 – 52.80	12	30.03	16.24 – 48.72	10	21.75	9.82 – 41.51	7	0.53
Chronicity	4.53	2.38 – 8.45	12	3.44	1.70 – 6.81	10	2.47	1.09 – 5.48	7	0.44
Wastage	3.37	1.63 – 6.82	9	2.4	1.06 – 5.32	7	2.15	0.90 – 5.04	6	0.66
Railers	5.13	2.84 – 9.07	13	2.98	1.43 – 6.11	8	2.35	1.02 – 5.33	6	0.22
Total Removals	13.33	8.99 – 19.32	32	10.32	6.70 – 15.57	26	8.88	5.57 – 13.87	22	0.30
Mortality, %										
Total Mortality	6.19	3.48 – 10.76	15	6.05	3.41 – 10.51	15	5.69	3.14 – 10.09	14	0.97
BRD Mortality	5.25	2.82 – 9.57	13	5.59	3.07 – 9.96	14	3.98	1.99 – 7.80	10	0.70
Other Mortality	0.84	0.20 – 3.45	2	0.41	0.06 – 2.92	1	1.65	0.58 – 4.60	4	0.41
Days on feed from enrollment to any death	26.53	17.76 – 35.31	19	23.47	14.69 – 32.24	16	13.50	4.42 – 22.58	15	0.11
Days on feed from enrollment to BRD death	25.85	16.59 – 35.11	16	24.79	15.86 – 33.71	15	11.80	1.24 – 22.36	11	0.10

*A randomized clinical trial at a commercial feedlot in Kansas; animals randomly assigned to one of the 3 experimental treatments (macrolide antibiotics).

[†]Tulathromycin (Arovyn[®]; Merck Animal Health, Madison, NJ) administered subcutaneously.

[‡]Tulathromycin and ketoprofen (Draxxin KP[®]; Zoetis Animal Health, Parsippany, NJ) administered subcutaneously.

[§]Tildipirosin (Zuprevo[®]; Merck Animal Health, Madison, NJ) administered subcutaneously.

^{||}Steers and heifers requiring a second treatment at any time for BRD were administered florfenicol (Nuflor[®]; Merck Animal Health, Madison, NJ)

^{||}Steers and heifers requiring a third treatment at any time for BRD were administered danofloxacin (Advocin[®]; Zoetis Animal Health, Parsippany, NJ)

Table 4.5. Model-adjusted means and SEM for health outcomes observed during the first 100 days following treatment of feedlot cattle with tulathromycin (TUL), tulathromycin and ketoprofen (TUL+K), or tildipirosin (TIL) at first clinical signs of BRD first 100 d after enrollment.*

Items,	Treatment									<i>P</i> -value
	TUL [†]			TUL+K [‡]			TIL [§]			
	Mean	95% CI	<i>n</i>	Mean	95% CI	<i>n</i>	Mean	95% CI	<i>n</i>	
<i>Morbidity, %</i>										
Retreatment Risk (treated twice)	23.51	17.41 – 30.94	63	25.03	18.76 – 32.56	67	22.96	16.95 – 30.33	63	0.86
First Treatment Success,										
No retreatment and no death	70.92	63.14 – 77.63	158	72.40	64.84 – 78.87	166	71.70	63.97 – 78.33	162	0.94
No retreatment and no BRD death	72.32	64.59 – 78.92	161	72.89	65.30 – 79.35	167	73.14	65.47 – 79.64	165	0.98
First Treatment Failure,										
Retreatment and/or any death	29.08	22.37 – 36.86	74	27.6	21.13 – 35.16	71	28.30	21.67 – 36.03	73	0.94
Retreatment and/or BRD death	27.68	21.08 – 35.41	71	27.11	20.65 – 34.70	70	26.86	20.36 – 34.53	70	0.98
Second Retreatment [¶]	53.4	39.65 – 66.66	35	54.26	40.63 – 67.27	37	50.58	36.59 – 64.48	32	0.92
Third Retreatment	45.04	26.99 – 64.49	16	32.27	17.07 – 52.46	12	20.52	8.75 – 41.01	8	0.14
Chronicity	6.06	3.42 – 10.52	16	4.01	2.09 – 7.56	12	2.76	1.28 – 5.86	8	0.18
Wastage	4.11	2.11 – 7.86	11	2.97	1.42 – 6.09	9	2.46	1.09 – 5.47	7	0.55
Railers	4.97	2.74 – 8.85	13	3.89	2.04 – 7.30	11	3.38	1.68 – 6.71	9	0.65
Total Removals	14.52	9.95 – 20.70	35	11.33	7.50 – 16.76	29	10.01	6.44 – 15.23	25	0.31
<i>Mortality, %</i>										
Total Mortality	6.19	3.48 – 10.76	19	6.05	3.41 – 10.51	16	5.69	3.14 – 10.09	15	0.97
BRD Mortality	6.61	3.72 – 11.47	16	6.18	3.44 – 10.85	15	4.45	2.28 – 8.50	11	0.57
Other Mortality	1.11	0.32 – 3.77	3	0.37	0.05 – 2.72	1	1.48	0.50 – 4.32	4	0.47
Days on feed from enrollment to any death	38.11	26.55 - 49.67	15	26.31	13.72 - 38.91	15	18.80	5.79 - 31.81	14	0.09
Days on feed from enrollment to BRD death	37.38	24.25 - 50.50	13	27.73	14.17 - 41.29	14	19.18	3.35 - 35.02	10	0.21

*A randomized clinical trial at a commercial feedlot in Kansas; animals randomly assigned to one of the 3 experimental treatments (macrolide antibiotics).

[†]Tulathromycin (Arovyn[®]; Merck Animal Health, Madison, NJ) administered subcutaneously.

[‡]Tulathromycin and ketoprofen (Draxxin KP[®]; Zoetis Animal Health, Parsippany, NJ) administered subcutaneously.

[§]Tildipirosin (Zuprevo[®]; Merck Animal Health, Madison, NJ) administered subcutaneously.

^{||}Steers and heifers requiring a second treatment at any time for BRD were administered florfenicol (Nuflor[®]; Merck Animal Health, Madison, NJ)

[¶]Steers and heifers requiring a third treatment at any time for BRD were administered danofloxacin (Advocin[®]; Zoetis Animal Health, Parsippany, NJ)

Table 4.6. Model adjusted means and standard errors of the means (SEM) for subsequent health outcomes of feedlot cattle randomly assigned either tulathromycin (TUL), tulathromycin and ketoprofen (TUL+K), or tildipirosin (TIL) treatments upon first clinical signs of BRD through closeout.*

Items,	Treatment									P-value
	TUL [†]			TUL+K [‡]			TIL [§]			
	Mean	95% CI	n	Mean	95% CI	n	Mean	95% CI	n	
<i>Morbidity, %</i>										
Retreatment Risk (treated twice)	23.54	17.45 – 30.96	63	25.41	19.10 – 32.96	68	22.94	16.94 – 30.29	63	0.81
First Treatment Success,										
No retreatment and no death	70.52	62.70 – 77.30	157	71.70	64.07 – 78.27	164	71.89	64.16 – 78.50	162	0.94
No retreatment and no BRD death	71.87	64.12 – 78.51	160	72.57	64.96 – 79.05	166	73.23	65.59 – 79.70	165	0.95
First Treatment Failure,										
Retreatment and/or any death	29.48	22.70 – 37.30	75	28.30	21.73 – 35.93	73	28.11	21.50 – 35.84	73	0.94
Retreatment and/or BRD death	28.13	21.49 – 35.88	72	27.43	20.95 – 35.04	71	26.77	20.30 – 34.41	70	0.95
Second Retreatment [¶]	53.45	39.75 – 66.65	35	53.46	40.01 – 66.42	37	50.48	36.56 – 64.33	32	0.93
Third Retreatment	45.23	26.47 – 65.44	16	32.23	16.52 – 53.34	12	22.54	9.66 – 44.20	9	0.20
Chronicity	5.99	3.36 – 10.44	16	3.89	2.01 – 7.39	12	3.07	1.47 – 6.30	9	0.25
Wastage	4.02	2.05 – 7.75	11	2.83	1.34 – 5.88	9	2.74	1.26 – 5.88	8	0.65
Railers	4.91	2.69 – 8.78	13	4.11	2.19 – 7.57	12	3.69	1.88 – 7.12	10	0.78
Total Removals	14.81	10.14 – 21.12	36	11.83	7.87 – 17.42	31	10.18	6.55 – 15.48	26	0.31
<i>Mortality, %</i>										
Total Mortality	8.44	5.08 – 13.70	20	7.05	4.11 – 11.83	17	6.14	3.46 – 10.65	15	0.64
BRD Mortality	7.13	4.11 – 12.08	17	6.21	3.49 – 10.81	15	4.48	2.32 – 8.49	11	0.48
Other Mortality	1.15	0.34 – 3.82	3	0.77	0.18 – 3.19	2	1.52	0.53 – 4.34	4	0.73
Days on feed from enrollment to any death	45.00	29.40 – 60.60	20	32.82	15.90 – 49.75	17	18.80	0.78 – 36.82	15	0.10
Days on feed from enrollment to BRD death	45.53	29.20 – 61.86	17	27.73	10.35 – 61.86	15	19.18	–1.12 – 39.48	11	0.11

*A randomized clinical trial at a commercial feedlot in Kansas; animals randomly assigned to one of the 3 experimental treatments (macrolide antibiotics).

[†]Tulathromycin (Arovyn[®]; Merck Animal Health, Madison, NJ) administered subcutaneously.

[‡]Tulathromycin and ketoprofen (Draxxin KP[®]; Zoetis Animal Health, Parsippany, NJ) administered subcutaneously.

[§]Tildipirosin (Zuprevo[®]; Merck Animal Health, Madison, NJ) administered subcutaneously.

^{||}Steers and heifers requiring a second treatment at any time for BRD were administered florfenicol (Nuflor[®]; Merck Animal Health, Madison, NJ)

[¶]Steers and heifers requiring a third treatment at any time for BRD were administered danofloxacin (Advocin[®]; Zoetis Animal Health, Parsippany, NJ)

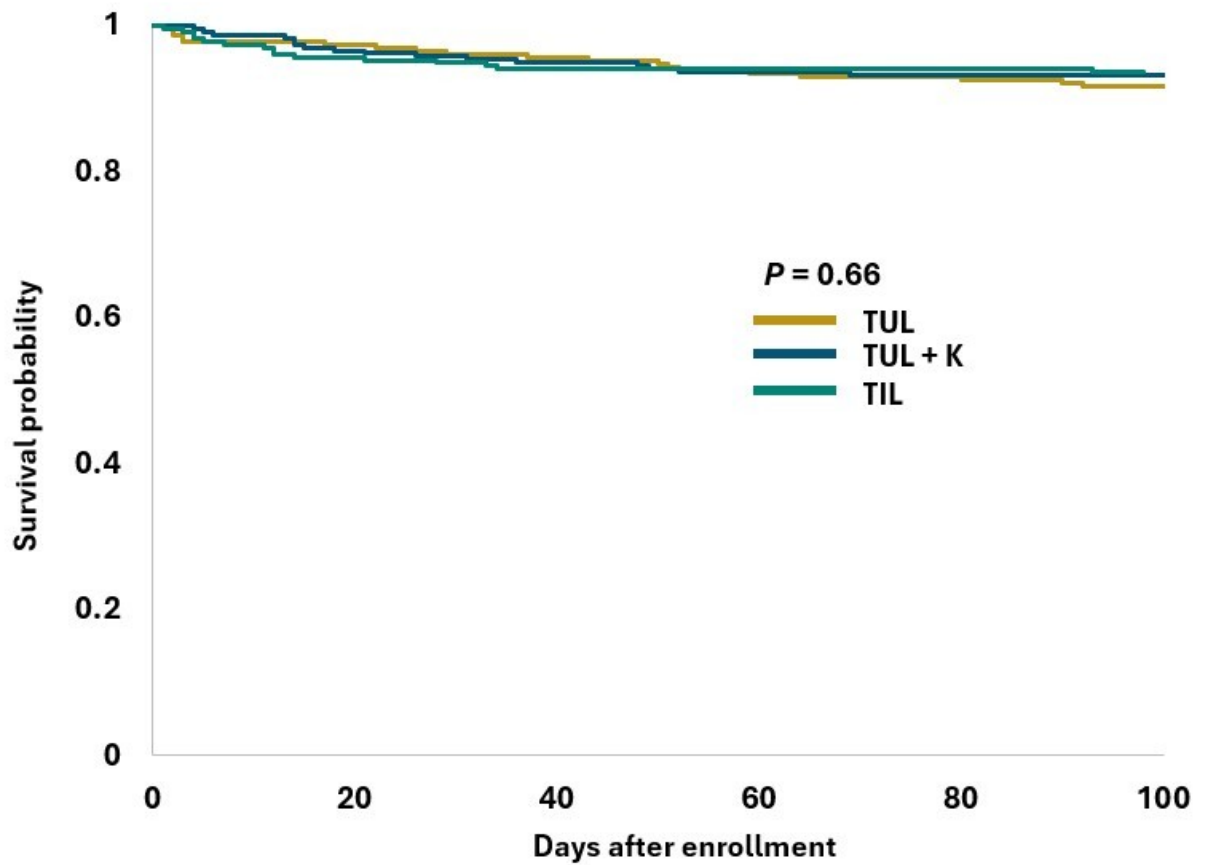


Figure 4.1. Kaplan–Meier survival curves showing the probability of survival from the day of treatment allocation for feedlot cattle diagnosed with first clinical signs of BRD and treated with tulathromycin (TUL; $n = 232$), tulathromycin plus ketoprofen (TUL+K; $n = 237$), or tildipirosin (TIL; $n = 235$). Survival probabilities did not differ among treatment groups (log-rank test: $P = 0.66$).

1 **Chapter 5 - Animal health and performance as drivers of**
2 **greenhouse gas emission intensity of beef cattle from post-weaning**
3 **production systems**

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12
13 **Abstract**

14 Health challenges in weaned beef cattle such as bovine respiratory disease, lameness, and
15 parasitism impair growth performance and feed efficiency, reducing the efficiency with which
16 inputs are converted into saleable beef and thereby increasing greenhouse gas (GHG) emissions
17 intensity (EI). Together, these relationships demonstrate that animal health is a primary driver of
18 both production efficiency and environmental performance in beef systems. This narrative
19 review synthesizes published literature and corresponding evidence to document how health and
20 performance shape emissions from weaning through harvest, and then describes the development
21 and application of a feedlot-level emissions calculator that generates pen-level estimates of EI
22 from routinely collected production data. Across studies, reductions in average daily gain, feed
23 efficiency, and survival consistently increased EI, whereas interventions that improved animal

health and performance lowered EI. Applied examples using data from research in commercial production systems demonstrated that strategies such as arrival metaphylaxis, automated disease detection, parasite control in grazing cattle, and growth-promoting technologies reduced EI by improving growth, feed efficiency, and survival. These findings highlight that interventions to improve cattle health and performance also can function as practical strategies for reducing the environmental footprint of beef production.

Key Words: beef cattle, animal health, growth performance, feed efficiency, greenhouse gas emissions, emissions intensity, feedlot finishing, sustainability, production systems, North America

Introduction

The United States contributed approximately 20% of the global beef supply in 2025, making it the world's leading beef producer (USDA FAS, 2026). Looking ahead, the global population is projected to increase from over 7 billion to approximately 9.6 billion by 2050. Combined with rising per capita incomes in low-income nations, this growth is expected to increase global food demand by nearly 49% (FAO, 2017). Meeting this demand will require continued improvements in the efficiency and sustainability of food production systems, including beef.

In 2024, direct emissions from beef production accounted for approximately 2.2% of total U.S. greenhouse gas (GHG) emissions (EPA, 2024). While this is a relatively small contribution, these emissions have been decreasing slowly over the last several decades, corresponding with a decline in beef cattle populations (Beck et al., 2023). During this same period, U.S. beef production has achieved substantial improvements in production efficiency, producing more beef with fewer cattle. This has resulted in marked improvements in the emission intensity (emissions per unit of product produced) of the final beef product (Capper, 2011; Crawford et al., 2022). Compared with production in 1977, beef production in 2007 required less feed, land, and water

and produced 16% fewer GHG emissions per kg of beef (Capper, 2011). These improvements were driven largely by advances in cattle growth rates, technology advancements, slaughter weights, and crop yields (Capper, 2020; Crawford et al., 2022).

Sustainability in livestock systems encompasses environmental responsibility, economic viability, and social acceptability, including public expectations related to animal welfare, food safety, and transparency (de Wit et al., 1995; United Nations, 2005). Animal health represents an important constraint to sustainability in beef production systems. Globally, more than 20% of animal protein is lost to disease (OIE, 2015). Diseases such as bovine respiratory disease (BRD), parasitism, and lameness conditions (e.g., foot rot) reduce cattle growth and feed efficiency, contributing to economic inefficiencies and sustainability challenges across livestock systems (Husu-Kallio, 2008; Cervantes, 2015; Sneeringer et al., 2015). Although the magnitude of disease impacts varies, affected animals typically perform below their healthy counterparts, limiting the efficiency with which inputs are converted into saleable beef. Addressing animal health challenges therefore has implications beyond productivity, shaping environmental outcomes and the overall sustainability of beef production systems.

Across a beef animal's lifetime, the cow-calf phase accounts for the majority of total GHG emissions, typically representing approximately 70 to 80% of lifecycle emissions, whereas post-weaning phases, including stocker and feedlot production, contribute the remaining proportion (Beauchemin et al., 2010; Rotz et al., 2019; McAtee et al., 2025). Although the feedlot phase represents a smaller proportion of total emissions, it is a highly managed stage of production where targeted interventions can meaningfully influence emissions outcomes.

Accordingly, the use of growth-promoting technologies such as anabolic implants, ionophores,

71 β -adrenergic agonists, and antimicrobials has been widespread in commercial feedlot systems to
72 improve animal health, performance, and/or feed efficiency (Wileman et al., 2009).

73 Together, these considerations highlight the interconnected nature of animal health,
74 productivity, and environmental outcomes in beef production systems. Therefore, the objectives
75 of this paper are to (1) systematically characterize the relationships between cattle health,
76 performance, and GHG emissions from weaning through harvest, and (2) quantify the extent to
77 which management and health interventions that improve performance influence emissions and
78 support sustainable beef production. To achieve this objective, we first synthesize existing
79 evidence describing the effects of animal health on cattle performance and productivity. We then
80 describe the development and scope of a feedlot-level emissions calculator designed to estimate
81 emissions intensity (EI) using routinely collected production data. Finally, we apply this
82 calculator to real-world examples to demonstrate how differences in cattle health interventions
83 and disease detection strategies translate into measurable differences in EI through their effects
84 on animal health, performance, and survival. This article is a narrative review that integrates
85 published literature with applied modeling to develop a systems-based framework linking cattle
86 health, performance, and EI.

87 **Health impacts on performance and productivity**

88 Despite substantial gains in efficiency within U.S. beef production systems, animal health
89 challenges continue to constrain productivity. Diseases can reduce cattle growth and feed
90 efficiency, contributing to economic inefficiencies and sustainability challenges across livestock
91 systems (Husu-Kallio, 2008; Cervantes, 2015; Sneeringer et al., 2015). In this context, animal
92 performance refers to individual-level biological outcomes such as growth rate, feed intake, feed
93 efficiency, health status, reproductive success, and survival, whereas productivity reflects the

94 system-level conversion of inputs into saleable beef. Animal health directly influences
95 performance, and when aggregated across cattle populations, these performance effects translate
96 into reduced productivity of beef production systems.

97 Health challenges reduce the efficiency with which feedlot production systems convert
98 inputs into edible output by lowering growth rate and carcass yield and increasing days on feed
99 (DOF); further, mortality represents a complete loss of all resources invested in cattle
100 maintenance and growth (Capper, 2020). Thus, health challenges impair not only individual-
101 animal performance but also feed efficiency, carcass value, and the overall sustainability of
102 feedlot production systems (Capper, 2020).

103 Cattle health is closely linked to feeding behavior and performance. A decline in dry
104 matter intake (DMI) is a consistent biological response in calves exhibiting clinical signs of
105 illness (Krehbiel, 2020). Healthy, well-adapted cattle exposed to fewer stressors generally
106 consume more feed than newly received, highly stressed animals; however, in commercial
107 systems the precise timing between disease onset and reductions in feed intake remains difficult
108 to pinpoint (Krehbiel, 2020). Despite this uncertainty, monitoring feeding behavior using
109 precision technologies has shown that changes in feeding patterns and DMI can be used to
110 predict which animals will later require treatment for BRD (Wolfger et al., 2014; Jackson et al.,
111 2016). Beyond clinical disease, environmental stressors such as heat stress also impair feeding
112 behavior and growth performance through similar mechanisms; under heat stress, cattle reduce
113 feed intake to limit metabolic heat production, leading to decreased average daily body weight
114 gain (ADG; Hahn, 1999; Mitloehner et al., 2001). These intake-driven performance losses are
115 similar to those observed during health challenges, indicating that disruptions to feed intake

represent a key pathway through which health stressors impair growth and efficiency in beef production systems.

A wide range of disease syndromes contribute to these losses, and most share similar mechanisms: reduced feed intake, impaired nutrient use, pain or lameness, and, in severe cases, death (Table 2). Among these conditions, BRD is the most consequential health syndrome in feedlot production systems, accounting for the largest proportional share of feedlot morbidity and mortality (Engler et al., 2014; Smith, 1998) and is therefore discussed in greater detail below. The following sections provide brief examples of major disease categories affecting performance, with comprehensive disease coverage summarized in Table 2 and quantitative treatment-frequency effects summarized in Table 1.

Bovine respiratory disease

Bovine respiratory disease has consistently reduced cattle performance across multiple studies as demonstrated in the following section. Animals treated once for BRD generally exhibit modest decreases in average daily gain (ADG; -2 to -3%) compared with healthy, untreated cattle, while repeated treatments are associated with progressively larger reductions. Chronically ill animals, in particular, can experience ADG reductions exceeding -15% , related to both the frequency and severity of disease events (Holland et al., 2010; Wilson et al., 2016; Brooks et al., 2011; Blakebrough-Hall et al., 2020; Montgomery et al., 2009; Cernicchiaro et al., 2013; Gardner et al., 1999; Thomson et al., 2012; Faber et al., 1996; Reinhardt et al., 2009; Pickett et al., 2023). Final body weight (FBW) and hot carcass weight (HCW) follow similar patterns, with reductions becoming more pronounced as treatment frequency increases. Cattle treated for BRD with a single treatment typically show small decreases in FBW (-1 to -2%) and HCW (-1 to -2%), whereas animals treated multiple times or classified as chronically ill may exhibit

substantially larger reductions, sometimes exceeding –10% in HCW (Holland et al., 2010; Wilson et al., 2016; Brooks et al., 2011; Blakebrough-Hall et al., 2020; Montgomery et al., 2009; Cernicchiaro et al., 2013; Gardner et al., 1999; Thomson et al., 2012; Faber et al., 1996; Reinhardt et al., 2009; Picket et al., 2023; Schneider et al., 2009; Snowden et al., 2007; Garcia et al., 2009). Cumulative treatment analyses further highlight the negative impact of repeated BRD episodes. Across studies, ADG, FBW, and HCW decreased progressively with ≥ 1 , ≥ 2 , and ≥ 3 treatments, underscoring the compounding effects of disease severity and recurrence (Faber et al., 1996; Gardner et al., 1999; Snowden et al., 2007; Garcia et al., 2009; Reinhardt et al., 2009; Schneider et al., 2009; Thomson et al., 2012; Cernicchiaro et al., 2013; Wilson et al., 2016; Blakebrough-Hall et al., 2020; Picket et al., 2023).

Lameness

Lameness from all causes represents approximately 16% of feedlot morbidities and is associated with reductions in ADG and increased DOF (Terrell et al., 2017). Affected cattle reduce their feed intake and make fewer visits to the bunk, in part because they are less able to compete with healthy pen mates (Jensen and Proudfoot, 2017). Foot rot, injuries, and toe abscesses are among the most common causes of lameness in feedlot cattle (Miskimins, 2002; Van Metre et al., 2005). Toe abscesses develop when the weight-bearing surface of the outer hoof wall becomes worn down enough to penetrate the junction between the laminar corium and the sole corium (the white line). Infection from environmental bacteria then tracks upward beneath the laminar corium and eventually breaks out at the top of the hoof, resulting in pain and impaired mobility (Griffin, 1998). Foot rot (necrotic pododermatitis or interdigital necrobacillosis) is a common condition in feedlot cattle. Damage to the interdigital skin caused by excessive moisture, frozen ground, or very dry conditions increases susceptibility to infection

(Stokka et al., 2001). Cattle diagnosed with foot rot tend to gain weight more slowly and require additional days on feed to reach target harvest weight compared with unaffected animals. In feedlot steers, a single foot rot incident has been shown to reduce ADG from 1.30 to 1.27 kg/d, with cases occurring later in the feeding period further decreasing ADG by approximately 0.049 kg/d compared with non-affected cattle (Tibbetts et al., 2006). Foot rot also increases time required to reach harvest, with affected steers requiring approximately 5 additional days on feed overall and up to 14.3 additional days when onset occurs during the finishing phase (Tibbetts et al., 2006). Digital dermatitis is a multifactorial, polybacterial, and contagious foot disease characterized by inflammatory lesions on the plantar surface of the interdigital cleft (Orsel et al., 2017; Holzhauer et al., 2018) and has been shown to reduce ADG in feedlot cattle by approximately 0.11 to 0.17 kg/d during the finishing period (Cortes et al., 2021).

Parasitic disease

Parasitic infections can cause visible clinical signs such as anemia, diarrhea, and a rough hair coat, but even subclinical infections impair nutrient absorption and energy metabolism, ultimately reducing weight gain (Gibbs, 1982). These infections negatively affect the beef industry by reducing feed efficiency as a ratio of body weight gain to weight of feed (G:F), immune function, reproductive performance, liveweight, milk yield, calf output, and carcass weight (Strydom et al., 2023). Gastrointestinal and pulmonary nematodes, liver flukes, ticks, flies, lice, mites, and protozoal parasites all contribute to economic losses, with nematodes, trematodes, and ticks causing the greatest global economic impact in beef production (Strydom et al., 2023). Protozoal infections such as coccidiosis are among the most common parasitic diseases of cattle (Step et al., 2002). Coccidiosis is often considered a disease of confinement feeding operations; however, grazing stocker cattle (weaned calves grown on pasture prior to

185 feedlot finishing) also can be affected (Step and Smith, 2006). Animals with coccidiosis may
186 exhibit mild depression and reduced appetite or feed intake, contributing to impaired growth
187 performance (Step and Smith, 2006). Experimental infections have shown that untreated calves
188 can experience prolonged reductions in feed intake lasting up to 13 weeks and body weight
189 deficits of 22–27 kg during the post-infection growth period compared with uninfected or treated
190 calves (Fitzgerald and Mansfield, 1972). In addition, therapeutic control has been shown to
191 improve weight gain by approximately 50%, indicating substantial suppression of ADG in
192 untreated infected calves (Sinks et al., 1992). Gastrointestinal nematodes are globally widespread
193 and substantially reduce productivity by increasing time to slaughter weight (Fox et al., 2018).
194 Conservative, and now dated, estimates place their annual cost to the U.S. cattle industry at over
195 \$2 billion (Stromberg and Gasbarre, 2006). The most significant physiological effects of
196 nematode infection are reduced appetite, driven by gastrointestinal discomfort, immune
197 signaling, and altered hormonal regulation (Fox et al., 1993). Experimental nematode infection
198 has been shown to reduce feed intake by approximately 20–30% and suppress ADG from 0.174
199 kg/d in healthy animals to 0.007 kg/d in parasitized animals, resulting in substantially slower
200 growth and prolonged time to target weight (Fox et al., 2018). In addition, gastrointestinal
201 nematodes can impair immune function and reduce responsiveness to other infections or
202 vaccinations (Stromberg and Gasbarre, 2006). Liver flukes often cause subclinical reductions in
203 feed efficiency and growth that meaningfully affect productivity (Kaplan, 2001). Fluke infection
204 has been shown to reduce ADG in feedlot cattle by approximately 6%, reflecting depressed feed
205 conversion efficiency and slower growth during the feeding period (Malone et al., 1982). In
206 addition, fluke infection has been associated with reduced carcass weight due to tissue damage

and impaired liver function, with affected cattle exhibiting approximately 4 kg lower HCW compared with cattle with normal livers (Brown and Lawrence, 2010).

External parasites also contribute substantially to performance losses. Approximately 80% of the global cattle population is affected by ticks and tick-borne diseases (Burrow et al., 2019). Although blood loss contributes to production losses, tick infestation also alters appetite, digestion, and metabolism (Jonsson, 2006), with each engorging cattle tick associated with approximately 1.2 to 1.4 g of body weight loss in infested cattle (Jonsson, 2006). Stable flies further reduce weight gain and feed efficiency in cattle, with feeder cattle experiencing approximately 9 kg less body weight gain per animal per year under typical infestation levels (Taylor et al., 2012).

Nutritional, metabolic and other infectious diseases

Fescue toxicosis occurs when cattle graze tall fescue infected with the endophyte *Epichloë coenophiala* and consume ergot alkaloids. These alkaloids induce vasoconstriction through interactions with biogenic amine receptors, resulting in reduced peripheral blood flow (Klotz et al., 2012; 2013). Impaired blood flow disrupts thermoregulation, limiting the animal's ability to dissipate body heat, particularly under warm environmental conditions (Aiken et al., 2007; McClanahan et al., 2008). Exposure to ergot alkaloids during the stocker phase has been associated with reduced nutrient intake and markedly depressed growth performance, with cattle grazing toxic endophyte-infected tall fescue exhibiting ADG ranging from 0.31 to 0.56 kilograms per day, compared with 0.78 to 1.00 kilograms per day in cattle grazing non-toxic or endophyte-free tall fescue (Parish et al., 2003). Both frothy and free-gas bloat occur in weaned-calf (stocker and feedlot) systems and can affect cattle of any breed, age, or production background (Griffin, 1998; Step and Smith, 2006). Bloat typically occurs sporadically, with

losses arising from mortality and reduced feed intake that diminish overall production (Step and Smith, 2006). Although reduced intake and performance losses in surviving cattle are consistently noted, controlled studies quantifying the magnitude of feed intake or growth suppression attributable to bloat remain limited, in part because bloat is an acute and intermittent condition that is difficult to evaluate under controlled production settings (Cheng et al., 1998; Wang et al., 2012). Lactic acidosis, or grain overload, is a common condition in feedlot cattle, and a managed degree of acidosis is often inherent to achieving production goals in high-grain systems (Griffin, 1998). Cattle recovering from sustained ruminal acidosis may develop secondary conditions such as ruminitis, laminitis, or liver abscesses, which contribute to reduced feed intake and weight gain; however, the cumulative production impacts of these sequelae are difficult to quantify under controlled production settings due to the variable severity and episodic nature of acidosis (Nagaraja and Lechtenberg, 2007).

Pinkeye (infectious bovine keratoconjunctivitis) causes ocular discomfort and measurable reductions in weight gain in affected cattle. Calves experiencing pinkeye before weaning have been reported to exhibit 17–18 kg lower 205-day weaning weights, and bulls that experienced pinkeye had lower postweaning average daily gain (0.83 vs. 0.91 kg/d) compared with unaffected animals (Step and Smith, 2006). Anaplasmosis, an infectious disease transmitted by ticks, biting flies, or contaminated instruments, commonly results in weight loss and reduced weight gain in affected cattle (Aubry and Geale, 2011; Kocan et al., 2003). Although low weight gain is a recognized outcome of infection, few controlled studies have quantified the magnitude of production losses attributable to anaplasmosis under commercial conditions (Kocan et al., 2003; Ierardi, 2025).

All-morbidity synthesis across diseases

When morbidities are evaluated collectively, including BRD, lameness, digestive disorders, parasitic disease, and other conditions, similar performance patterns emerge, though average effects per event are often smaller than those observed for BRD alone. These patterns are summarized in Table 1. Across studies, cattle treated once for any morbidity exhibit modest reductions in ADG (-0.5 to -1%), FBW (-1 to -1.5%), and HCW (-0.1 to -0.5%) relative to healthy animals (Table 1; Roeber et al., 2001; Hands et al., 2012; Parish et al., 2012; Waggoner et al., 2007; Bloomberg et al., 2013; Jim et al., 1993; Gadberry and Troxel, 2006). As the number of morbidity events increases (≥ 2 or ≥ 3 treatments), ADG, FBW, and HCW decline progressively, reflecting the cumulative burden of repeated illness and therapeutic intervention (Parish et al., 2012; Hands et al., 2012; Waggoner et al., 2007; Bloomberg et al., 2013). Collectively, evidence from both disease-specific and all-morbidity analyses indicates that health challenges consistently reduce cattle growth and carcass performance. Across disease categories, reductions in feed intake, impaired nutrient utilization, prolonged DOF, and mortality translate individual-animal performance losses into reduced system-level efficiency.

Performance drivers of emission intensity

Emissions intensity is defined as the amount of GHG emissions, expressed as kilograms of carbon dioxide equivalents ($\text{kg CO}_2\text{e}$), produced per kilogram of FBW or beef produced (McAtee et al., 2025). In beef production systems, EI reflects the efficiency with which feed and other inputs are converted into saleable beef and is therefore strongly influenced by cattle performance (Capper, 2011; Capper, 2020). Within feedlot systems, variation in growth rate, G:F, and DOF directly alters cumulative maintenance requirements and total feed inputs per unit of beef produced, making performance traits such as ADG and G:F key drivers of EI (Capper,

2020; McAtee et al., 2025). Health-related reductions in cattle performance have direct implications for GHG emissions because EI is strongly influenced by ADG and G:F (McAtee et al., 2025). When disease reduces ADG, G:F, or survival, cattle require more DOF and greater total feed inputs per unit of beef produced to get to an optimal endpoint, increasing lifetime EI (McAtee et al., 2025). Thus, performance losses associated with health challenges scale directly into environmental inefficiency at the system level.

Growth rate and emissions intensity

Improvements in cattle growth performance have long been recognized as a primary mechanism for reducing EI in beef production systems, as faster growth dilutes maintenance-related emissions across greater productive output (Capper et al., 2009; Legesse et al., 2016; Beauchemin et al., 2020). Increased ADG shortens time on feed and reduces the cumulative emissions required to produce a unit of beef, resulting in lower EI on a per-unit-of-production basis (Boadi et al., 2004; Monteny et al., 2006; Capper and Hayes, 2012). Previous work demonstrates that improvements in feedlot cattle health, G:F, and ADG could substantially reduce EI (McAtee et al., 2025). Feedlot cattle pens with lower ADG exhibited higher estimated lifetime EI, and the relationship between ADG and EI was further influenced by sex and seasonal factors (McAtee et al., 2025). For both steers and heifers, EI decreased as ADG increased, with the highest ADG group (≥ 1.93 kg/d) producing approximately 15% lower EI than the lowest ADG group (< 1.13 kg/d). Across all seasons, higher ADG was consistently associated with reduced EI, with reductions ranging from approximately 13% to 17% in the highest ADG groups compared to the lowest (McAtee et al., 2025). These findings indicate that slower growth, which is commonly observed in cattle experiencing health challenges, extends time on feed and increases the accumulation of maintenance-related emissions relative to pounds produced,

thereby increasing EI. This biological relationship is consistent with previous research demonstrating that increased ADG is associated with reduced enteric methane (CH₄) emissions and lower EI through improved efficiency of gain (Min et al., 2022; Beauchemin et al., 2020).

Feed efficiency and emissions intensity

Feed efficiency has similarly been identified as a key determinant of EI in beef production systems, as improvements in G:F reduce feed requirements, CH₄ production, and total emissions per unit of beef produced (Capper et al., 2009; Beauchemin et al., 2020). Pens with lower G:F demonstrated greater lifetime EI, mirroring the relationship observed for ADG (McAtee et al., 2025). The association between G:F and EI was found to be modified by both sex and season. Within each sex, EI declined as G:F improved, with the most efficient pens (≥ 0.175) exhibiting approximately 15–18% lower emissions than the least efficient pens (< 0.10). Seasonal trends were consistent, with higher G:F values associated with reduced EI, ranging from approximately 10% lower in winter to more than 20% lower in summer (McAtee et al., 2025). Reductions in G:F are a common consequence of clinical disease and other health challenges, and these findings reinforce that inefficiencies in nutrient utilization translate directly into higher EI. This pattern aligns with previous work demonstrating that improved feed efficiency reduces EI by increasing the proportion of consumed energy retained as productive gain rather than lost as enteric CH₄ (Coopridge et al., 2011; Beauchemin et al., 2020).

Production efficiency interventions and emissions outcomes

Production technologies that enhance cattle performance further illustrate the link between performance and emissions outcomes. Growth-enhancing technologies have been shown to improve ADG, DMI, and G:F, thereby improving resource utilization and profitability while reducing EI (Wileman et al., 2009; Swenson et al., 2025). Although these technologies

also involve ethical, regulatory, and consumer perception considerations, their effects on performance provide a clear pathway through which management interventions influence emissions outcomes (Swenson et al., 2025). The evolution of available growth technologies over time highlights their cumulative impact on both performance and emissions. In 1990, commonly available technologies included estradiol-based implants and the ionophore monensin, whereas by 2020, feedlot systems routinely incorporated combination implants containing trenbolone acetate and estradiol, monensin, and ractopamine hydrochloride during the final 28 to 42 DOF (Crawford et al., 2022). In both 1990 and 2020 production scenarios, the use of available growth technologies increased FBW, ADG, G:F, and HCW compared with systems that did not employ these technologies (Crawford et al., 2022). Despite increases in initial and FBW, DMI, and total DOF in 2020 relative to 1990, the use of growth technologies in both production periods resulted in lower total GHG emissions per animal, expressed as carbon dioxide equivalents (CO₂e) (Crawford et al., 2022). Similarly, steers receiving implants during both the stocker and feedlot phases produced lower lifetime CO₂e emissions per animal than cattle managed under natural programs that did not administer implants (Stackhouse et al., 2012). Within the class of beta-adrenergic options, ractopamine hydrochloride is primarily associated with increased weight gain, improved feed efficiency, and greater carcass leanness, while lubabegron is a high-performing beta-modulator that also improves growth performance and feed efficiency, with additional reductions in ammonia emissions. Comparative evaluations indicate that cattle fed lubabegron also exhibit improved growth performance and G:F, resulting in a 6.2% reduction in estimated CO₂e emissions per unit of carcass weight compared with cattle receiving ractopamine hydrochloride (McAttee et al., 2024).

Collectively, available evidence indicates that conventional management practices, including the use of anabolic implants, ionophores, melengestrol acetate, and beta-adrenergic agonists, improve feedlot cattle performance while reducing the environmental footprint of beef production (Stackhouse et al., 2012; Swenson et al., 2025). Together, these findings demonstrate that improvements in growth rate and G:F, whether achieved through health management or targeted production technologies, can meaningfully reduce EI. While performance metrics such as ADG and G:F capture key drivers of EI, the extent to which health-related emissions are reflected depends on how EI is calculated, including whether intake- or output-based denominators are used (e.g., including versus excluding dead and removed animals) and whether metrics are evaluated at the individual-animal or pen-aggregate level. Health challenges can further amplify emissions through increased disease burden and mortality, effects that may be incompletely represented in performance measures alone, particularly when emissions associated with non-surviving animals are excluded from output-based calculations.

Impacts of health-related performance losses on emissions intensity

Disease burden and mortality represent integrated outcomes of health-related performance losses and provide an additional pathway through which cattle health influences EI (Husu-Kallio, 2008; Cervantes, 2015; Sneeringer et al., 2015; Capper, 2020). Emissions intensity reflects cumulative feed use and maintenance requirements relative to output, meaning that health-related performance losses have direct implications for GHG emissions.

Beyond their effects on growth and G:F, health challenges also influence emissions through increased disease burden and mortality (Beck et al., 2026). Treatment intensity reflects both the frequency and severity of disease events, while mortality represents a complete loss of all emissions associated with maintenance and growth that are not recovered through saleable

beef (Capper, 2020). Evaluating EI in relation to health burden and survival therefore provides critical insight into how animal health shapes environmental outcomes (OIE, 2015; McAtee et al., 2025).

Disease burden and emissions intensity

Total medicine cost per initial number of animals in a feedlot pen (n), used as a proxy for disease burden, was positively associated with estimated lifetime EI across specific seasons and arrival body weight classes (McAtee et al., 2025). Across all seasons, higher medicine costs in lighter arrival body weight categories were associated with proportionally greater increases in EI compared with heavier arrival body weights. Across all arrival body weight categories, EI was lowest among cattle with medicine costs below \$16/animal (13.56 kg CO₂e/kg FBW) and increased progressively with higher treatment costs. Pens with medicine costs $\geq$ \$55/animal exhibited approximately 6% higher EI relative to those with costs below \$16/animal (McAtee et al., 2025). These results suggest that increasing disease burden, reflecting both frequency and severity of health challenges, corresponds with progressively higher EI at the pen level. Emissions intensity reflects cumulative feed use, growth performance, and survival, and thus the observed associations represent integrated effects of disease burden rather than effects independent of ADG or G:F.

Mortality and emissions intensity

Mortality further exacerbates EI at the population level. Feedlot pens with higher cumulative mortality exhibited greater estimated lifetime EI across seasons and arrival body weight classes (McAtee et al., 2025). Pens with no mortalities had the lowest average EI (13.40 kg CO₂e/kg FBW), whereas pens with $\geq$ 11% mortality exhibited the highest values (15.59 kg CO₂e/kg FBW), representing a 16.3% increase. Within mortality categories, lighter arrival

bodyweight cattle consistently showed higher EI than heavier cattle, and EI tended to be highest during summer and lowest during spring across body weight classes (McAtee et al., 2025). Consistent with these findings, life cycle assessment research indicates that mortality contributes measurably to total feedlot GHG emissions; Beck et al. (2026) reported that mortality accounted for approximately 0.9% to 7.5% of total feedlot-sector GHG emissions in native beef and beef × dairy crossbred steers under varying growing regimens. Given that EI reflects feed use, growth, and survival, these associations represent integrated production effects rather than performance-adjusted estimates.

These findings demonstrate that cattle health, performance, and EI are tightly interconnected within feedlot production systems. Health challenges reduce ADG, G:F, and survival, which directly impair biological performance and indirectly increase EI by extending days on feed and increasing cumulative maintenance requirements. Improvements in performance metrics such as ADG and G:F consistently correspond with lower EI, highlighting performance as a key intermediary between health and environmental outcomes. Beyond performance alone, indicators of disease burden and mortality may further exacerbate EI by introducing inefficiencies that extend beyond observed changes in ADG and G:F, particularly when mortality results in maintenance emissions without corresponding output. Collectively, this evidence underscores that strategies aimed at improving cattle health offer compounding benefits, simultaneously enhancing productivity, reducing EI, and strengthening the overall sustainability of beef production systems.

Estimating greenhouse gas emissions in post-weaning production systems

Greenhouse gas emissions from cattle can be quantified using either direct measurement or estimation approaches. Direct measurement techniques for enteric CH₄ include respiration

chambers, the sulfur hexafluoride (SF₆) tracer technique, breath sampling during feeding or milking, the GreenFeed system, and laser CH₄ detectors (Garnsworthy et al., 2019). While these methods provide valuable insight into CH₄ production at the individual-animal level, they are not practical for quantifying emissions at the multiple pen or feedlot scale, which is the level at which cattle health, management, and production decisions are implemented and evaluated in commercial feedlot systems.

Methane emissions from cattle are strongly influenced by DMI, which serves as a primary biological driver of enteric CH₄ production (Johnson and Johnson, 1995; Mills et al., 2003; Ellis et al., 2007). As a result, changes in intake associated with health status or management practices can partially explain observed differences in CH₄ emissions. Although environmental respiration chambers are considered the most precise method for measuring gaseous emissions from livestock, animal behavior and feed intake are often altered during chamber housing, which can affect performance and DMI and limit the applicability of these measurements to commercial production systems (Kebreab et al., 2006). Consequently, emissions from populations of beef cattle in production systems are most commonly estimated using modeling approaches, typically through life cycle assessment (LCA), rather than measured directly. A range of models have been developed to estimate CH₄ emissions at global, national, and farm scales, with the Intergovernmental Panel on Climate Change (IPCC) framework serving as the international standard for emissions accounting (Storm et al., 2012). These estimation-based approaches allow emissions to be quantified using routinely collected production data, enabling evaluation of management practices and interventions in real-world production settings. These approaches are not intended to replicate direct animal-level measurements, but instead provide consistent, comparative estimates of emissions across

management scenarios. In practice, emissions can be described at multiple scales, including individual-animal measurements, pen- or cohort-level estimates used for management decisions, and whole-system LCA estimates reported at regional or national scales. Given these methodological and scale considerations, applied evaluation of emissions within commercial feedlot systems requires estimation tools that align with routinely collected production data.

Beef cattle emissions calculators

The beef cattle feedlot emissions calculator

Purpose

The Beef Cattle Feedlot Emissions Calculator (BFEC; <https://www.vet.k-state.edu/research/centers-institutes/core/tools/BFEC>) was developed by Kansas State University to estimate GHG emissions from finishing beef cattle in feedlots, following guidelines established by the USDA. The tool is intended for use by cattle feeders and technical consultants to predict enteric CH₄ emissions and overall feedlot emissions, allowing comparative assessments of how production practices and health interventions influence sustainability outcomes. Emissions are expressed per kg of FBW to provide a standardized measure of GHG intensity relative to cattle weight at feedlot exit.

The BFEC is intended for pen- and feedlot-level application during the finishing phase, enabling consistent comparisons across treatments and management scenarios rather than generating full supply chain or national inventory estimates. In addition to comparing treatment groups within structured research trials, the calculator can be used operationally to track EI over time within a feedlot as health programs, cattle sourcing, diets, and management practices change across production cycles. The BFEC was developed by Kansas State University to address this applied need by estimating feedlot-level GHG emissions using standard production

and performance data. Rather than functioning as a full LCA or requiring direct emissions measurement, the calculator provides a transparent, scalable framework for estimating emissions within defined system boundaries using routinely collected commercial feedlot data. Accordingly, the calculator was designed to prioritize applicability to commercial operations while remaining consistent with established national and international emissions accounting frameworks.

Calculator framework and scope

The BFEC was used to estimate GHG emissions directly associated with feedlot cattle during the finishing phase. System boundaries were limited to on-site emissions from cattle and manure management, and the functional unit was defined as kilograms CO_{2e} per kilogram of FBW and HCW, enabling standardized comparisons across pens, treatments, and management strategies. Given regional differences in feed ingredient usage, sourcing, and production practices, these emissions were omitted from this version, but can easily be integrated into the model at the users discretion. Included emission sources consisted of enteric CH₄ produced during ruminal fermentation, CH₄ generated from anaerobic decomposition of manure, nitrous oxide (N₂O) emissions associated with manure management, and ammonia (NH₃) volatilization from urine and feces as a precursor to indirect N₂O emissions. Emissions associated with feed production and transport, feedlot energy use, capital goods and infrastructure, cattle production prior to feedlot entry, transportation of finished cattle, and post-feedlot processes are excluded to maintain alignment with available data and the applied feedlot focus of the calculator. The calculator incorporates standard feedlot production and performance data routinely collected in commercial and research settings, including: feed intake, diet formulation, animal inventory and weights, animal-days, removals and mortalities, harvested animal counts, FBW, and HCW.

Emissions can be estimated at the pen level to support evaluation of health interventions and management strategies. All GHG emissions are converted to CO₂e using 100-year global warming potential (GWP100) values from the IPCC Sixth Assessment Report (IPCC, 2023). Methodologies incorporated into the calculator are consistent with established frameworks from the USDA (2014), the Intergovernmental Panel on Climate Change (IPCC, 2019), and the U.S. Environmental Protection Agency (EPA, 2024). Further descriptions of emission factor selection, equations, and sector-specific assumptions are provided in Weir et al. (2026).

The beef cattle stocker emissions calculator

While the framework described here focuses on feedlot-based emissions estimation (BFEC), analogous approaches have been developed for grazing-based production systems. A Beef Cattle Stocker Emissions Calculator (BSEC; <https://www.vet.k-state.edu/research/centers-institutes/core/tools/BSEC>) was developed in parallel with the BFEC at Kansas State University with a similar objective, to estimate direct GHG associated with cattle performance and management, but with parameterization reflecting forage-based diets, grazing dynamics, and stocker-phase production systems. The BSEC incorporates differences in intake estimation, diet composition, and manure deposition patterns inherent to grazing systems, while maintaining a comparable structure for estimating enteric CH₄ and manure-related emissions. This distinction is particularly relevant given that several intervention strategies evaluated across the beef production continuum, including those applied during the stocker phase, may have downstream effects on both performance and emissions during finishing. Detailed methodology and validation of the BSEC are described by Weir et al. (2026), and its application enables a more comprehensive, lifecycle-oriented evaluation of health and management interventions across production phases.

Applied examples linking health interventions to emission outcomes

To illustrate the applied use of the BFEC, examples using commercial feedlot data are presented below. These examples demonstrate how differences in cattle health interventions and disease detection strategies translate into measurable differences in EI through their effects on animal health, performance, and survival. Together, these applications highlight how the calculator can be used to evaluate environmental tradeoffs associated with real-world health management decisions in feedlot systems. Although the BFEC is applied directly in the first example, subsequent interventions draw on previously published studies in which emissions outcomes were estimated using established modeling frameworks, illustrating how health and performance interventions influence EI across production contexts.

Intervention study 1: Arrival metaphylaxis for bovine respiratory disease management

Metaphylactic antimicrobial therapy at feedlot arrival is widely used in high-risk cattle populations and has been shown to effectively reduce BRD morbidity and mortality (Nickell and White, 2010; Ives and Richeson, 2015; Abell et al., 2017; O'Connor et al., 2019). Horton et al. (2024) evaluated metaphylaxis as a health intervention within a broader sustainability framework, recognizing that health programs involve tradeoffs across multiple stakeholder priorities rather than a single optimal solution. The objective of the study was to compare metaphylaxis and pull-and-treat (PT) BRD management strategies using identical antimicrobials, evaluating effects on animal health and wellbeing, antimicrobial use, cattle performance, carcass characteristics, economics, and GHG emissions. Medium-risk feedlot cattle were assigned to either a PT program, in which tulathromycin (Draxxin; Zoetis Animal Health, Parsippany, NJ, USA) was administered at first clinical BRD treatment, or a metaphylaxis (META) program, in

which all cattle received tulathromycin at initial processing. Greenhouse gas emissions were estimated using the UpLook 1.0 model (Elanco Animal Health), which integrates methodologies from the USDA (2014), IPCC (Dong et al., 2019), and U.S. EPA (2022), with emissions expressed as carbon dioxide equivalents (CO_{2e}). Cattle managed under the PT strategy experienced greater BRD morbidity (17.2% vs. 7.3%; $P < 0.01$) and higher total mortality (2.5% vs. 1.1%; $P = 0.03$) compared with META cattle. On a per-animal-enrolled basis, metaphylaxis was associated with greater final live weight ($P = 0.04$) and carcass weight ($P = 0.08$). Estimated lifetime CO_{2e} emissions were approximately 2% lower per unit of live weight for META cattle relative to PT cattle ($P = 0.09$). When performance was evaluated on a dead-and-removed-animals-included basis, metaphylaxis resulted in a 15-kg increase in final body weight and a 0.06-kg/d increase in average daily gain compared with PT ($P \leq 0.05$). Collectively, these results demonstrate how BRD management strategies influence health, performance, and EI, reinforcing the role of animal health interventions in shaping both productivity and sustainability outcomes in feedlot systems.

Intervention study 2: Bovine respiratory disease control and detection strategies

This example utilizes data from a previously published commercial feedlot trial (Schupbach et al., 2025). Full details of the study design and implementation are provided elsewhere (Schupbach et al., 2025); a brief summary is included here to contextualize the emissions analysis. The trial employed a 3×2 factorial design to evaluate three BRD control strategies in combination with two BRD detection approaches. BRD control strategies included: (1) a negative control, (2) a positive control consisting of whole-pen metaphylaxis with tildipirosin, and (3) a targeted BRD control program (TBCP) that used individualized risk predictions generated by a novel technology (Whisper On Arrival; Merck Animal Health) to

determine whether tildipirosin was administered to an individual based on a proprietary algorithm. The disease detection approaches consisted of either automated animal disease detection (ADD) using a continuous monitoring system (SenseHub Feedlot; Merck & Co., Inc., Rahway, NJ, USA and its affiliates) or conventional pen-rider (PR) observation. Beef calves sourced through auction markets were procured using standard commercial practices, transported to a single research location, and randomly assigned to one of six treatment combinations within each block. Animals were monitored through study completion (224 days). Pen-level production and health data were used as inputs to the BFEC to estimate emissions per kg of FBW and HCW. Linear mixed models were used to evaluate emissions outcomes, with BRD control strategy, disease detection method, and their interaction included as fixed effects and block included as a random intercept. No significant interactions between BRD control strategy and detection method were observed for emissions-related outcomes; thus treatment main effects are reported. Estimated CO₂e emissions during the feeding period are presented in Table 3.

No significant differences in EI were detected among BRD control strategies ($P \geq 0.12$). In contrast, the disease detection approach significantly influenced EI. Pens monitored using the ADD system exhibited a 3.1% reduction in emissions per kilogram of FBW ($P = 0.004$) and a 3.0% reduction per kilogram of HCW ($P = 0.006$) compared with conventional pen-riding. These reductions corresponded with previously reported improvements in animal health and performance. Whole-pen metaphylaxis reduced BRD morbidity, removals, and mortality relative to the negative control, while ADD enabled earlier disease detection, fewer removals, and lower mortality (Schupbach et al., 2025). Performance outcomes followed similar patterns, with positive control (whole-pen metaphylaxis) increasing ADG by 9% compared with the negative control and ADD increasing ADG by 6% compared with pen-riding (Schupbach et al.,

2025). Together, these results demonstrate how disease detection and control strategies that improve health and performance also can reduce EI. In addition, this approach illustrates the utility of the BFEC for evaluating sustainability outcomes associated with health management decisions in commercial feedlot systems.

Intervention study 3: Dewormer, implant, antimicrobial

Common growth-promoting technologies used in feeder cattle production include performance-enhancing antimicrobials and steroidal implants (Bretschneider et al., 2008). In addition, gastrointestinal nematode infections represent a substantial economic burden to the stocker sector, and anthelmintics such as fenbendazole are commonly administered for parasite control (Prichard et al., 1978). Weir et al. (2026) evaluated the effects of combined anthelmintic use, steroidal implants, and growth-promoting antimicrobial supplementation on growth performance in stocker steers. Secondary objectives included assessing carryover effects of stocker-phase management on subsequent feedlot finishing performance, with a final objective to quantify estimated direct GHG emissions, including enteric CH₄ and manure-related emissions, across treatment combinations. In this study, stocker steers were assigned to a 2 × 2 × 2 factorial design evaluating fenbendazole administration (Safe-Guard®; SG), bambermycin supplementation (Gainpro®; GP), and implantation with a growth-promoting implant (Revalor-G®; RG). All treatments were applied during the stocker phase, and cattle were maintained in their assigned treatment groups during subsequent finishing in a research feedlot. Greenhouse gas emissions during the stocker phase were estimated using the BSEC, with subsequent finishing-phase emissions estimated using the BFEC to capture carryover effects across production phases.

During the stocker phase, no significant two-way or three-way interactions were observed among treatments ($P > 0.10$). Steers administered fenbendazole (SG) exhibited greater FBW

(+3.2%; $P < 0.01$), total weight gain (TWG; +14%; $P < 0.01$), and ADG (+14%; $P < 0.01$) compared with steers that did not receive SG (Weir et al., 2026). Similarly, steers supplemented with bambarmycin (GP) achieved higher FBW (+2.0%; $P < 0.02$), TWG (+10%; $P < 0.01$), and ADG (+7.5%; $P < 0.01$) relative to non-supplemented steers (Weir et al., 2026). The largest performance responses were observed in steers implanted with a growth-promoting implant (RG), which resulted in higher FBW (+5.5%; $P < 0.01$), TWG (+20%; $P < 0.01$), and ADG (+20%; $P < 0.01$) compared with non-implanted steers (Weir et al., 2026). Improvements in growth performance during the stocker phase translated to reductions in EI, with decreases of 8.3% for SG, 6.4% for GP, and 13.2% for RG (Weir et al., 2026). Collectively, these findings demonstrate that growth-promoting technologies and anthelmintic strategies implemented during the stocker phase can simultaneously enhance cattle performance and reduce EI, and in this study the impact of each of those strategies was additive.

Carryover effects of stocker-phase treatments on finishing performance were less pronounced. Steers that received SG during the stocker phase had lower TWG during finishing ($P < 0.03$) compared with steers that did not receive SG. In contrast, steers previously implanted with RG had greater FBW at the end of finishing (+2.3%; $P < 0.01$). Emissions intensity per kilogram of weight gain during finishing was approximately 2% lower ($P \leq 0.01$) for steers that received either SG or RG during the stocker phase. No significant main effects of SG, GP, or RG were detected for combined emission intensity across the stocker and finishing phases ($P \geq 0.15$).

Recommended use of the beef cattle feedlot emissions calculator

The BFEC is intended for applied use as a comparative decision-support tool within feedlot finishing systems. The calculator is best used to evaluate relative differences in EI across pens, treatment groups, or management scenarios using routinely collected production and health

data. It is particularly well suited for assessing how changes in animal health, performance, survival, and management practices influence emissions expressed per unit of FBW or HCW. The calculator is not designed to replace direct CH₄ measurement techniques or to generate absolute emissions inventories at regional, national, or full supply-chain scales. Instead, results should be interpreted as modeled, system-bounded estimates that enable consistent comparisons across interventions and management strategies within commercial feedlot operations. When applied in this context, the calculator provides a transparent and scalable framework for integrating emissions outcomes into broader evaluations of animal health, productivity, and sustainability.

Implications & conclusion

The findings presented here reinforce that cattle health and performance are central drivers of environmental sustainability in feedlot systems. Animal health, productivity, and EI are not independent outcomes, but interdependent components of the same biological and management system. When clinical or subclinical disease reduces feed efficiency, growth rate, or carcass yield, then more feed, time, and resources are required per unit of beef produced, resulting in higher EI. Conversely, management practices and interventions that improve health and performance inherently reduce EI by improving the efficiency with which inputs are converted into saleable beef. Importantly, many of the interventions discussed in this paper are already widely used in commercial beef production. Targeted disease control strategies, precision health monitoring technologies, and nutrition or management programs are routinely implemented, and continually being developed to improve animal well-being and productivity. These results highlight that such practices also deliver meaningful environmental benefits, even when environmental outcomes are not their primary objective. Recognizing and quantifying

these co-benefits reframes animal health management as a sustainability strategy in addition to a welfare and economic imperative.

Integrating animal health more explicitly into sustainability frameworks represents an opportunity for continued progress in the beef sector. Historically, emissions reduction efforts have focused primarily on feed additives, diet formulation, and manure management. While these approaches remain important, the results presented here demonstrate that improvements in animal health and performance can yield comparable or complementary reductions in EI. Health-centered strategies align with all three pillars of sustainability by reducing environmental impact, improving economic efficiency, and supporting animal welfare and responsible stewardship. Looking forward, a systems-based approach that integrates health, productivity, and environmental outcomes will be essential for advancing feedlot sustainability. Data-driven tools such as the BFEC provide a mechanism to quantify the emissions implications of management decisions and to evaluate tradeoffs using routinely collected production data. Ultimately, sustainable beef production will depend not solely on the adoption of new practices, but also on a more holistic recognition of animal health as a cornerstone of productivity, environmental stewardship, and long-term industry resilience.

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Data availability

This review synthesizes published literature and includes modeled outputs generated using production data. The feedlot and stocker greenhouse gas emissions calculators described in this manuscript are publicly available at. Data generated during the applied analyses are available from the corresponding author upon reasonable request; however, some underlying datasets were derived from commercial feedlot records and technology platforms and are not publicly available due to confidentiality agreements.

Author contributions

All authors contributed to the conception and design of the manuscript. TM conducted the literature review, developed the feedlot emissions calculator, performed the analyses, and wrote the original draft of the manuscript. LT assisted with development of the emissions calculator. TM, DR, and LT reviewed and edited the manuscript and approved the final version.

Competing interests

The authors declare there are no competing interests.

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Tables

Table 5.1. Major health challenges affecting growth performance and efficiency outcomes in U.S. stocker and feedlot cattle*

Disease Category	Disease	Cause / Key Pathogens	Primary Performance Impacts
Respiratory	Bovine Respiratory Disease (BRD)	Viruses: <i>Bovine herpesvirus 1</i> (BHV-1), <i>Bovine viral diarrhea virus</i> (BVDV), <i>Bovine respiratory syncytial virus</i> (BRSV), <i>Parainfluenza-3 virus</i> (PI3), <i>Bovine coronavirus</i> (BCoV); bacteria: <i>Mannheimia haemolytica</i> , <i>Pasteurella multocida</i> , <i>Histophilus somni</i> , <i>Mycoplasma bovis</i>	Reduced ADG, reduced feed intake, increased DOF, increased mortality ¹
Gastrointestinal	Coccidiosis	<i>Eimeria</i> spp.	Reduced feed intake, reduced ADG, weight loss ²
Musculoskeletal / Lameness	Toe Abscesses	Environmental bacteria	Reduced mobility, reduced feed intake, reduced ADG ³
Musculoskeletal / Lameness	Foot Rot	<i>Fusobacterium necrophorum</i>	Reduced ADG, increased DOF ⁴
Musculoskeletal / Lameness	Digital Dermatitis	<i>Treponema</i> spp.	Reduced ADG, reduced mobility ⁵
Parasitic	Internal Parasites (GI nematodes)	<i>Ostertagia</i> , <i>Cooperia</i> , <i>Haemonchus</i>	Reduced intake, reduced ADG, increased DOF ⁶
Parasitic	Liver Flukes	<i>Fasciola hepatica</i>	Reduced ADG, reduced feed efficiency, decreased carcass weight ⁷
Parasitic	External Parasites (lice, flies, ticks)	Lice, stable flies, ticks (<i>various species</i>)	Reduced ADG, poor G:F efficiency ⁸
Nutritional / Metabolic	Bloat	Fermentation gas accumulation (frothy or free-gas)	Reduced feed intake, mortality in severe cases ⁹

Nutritional / Metabolic	Acidosis (grain overload)	Rapid fermentation of starch; low rumen pH	Reduced feed intake, reduced ADG, increased morbidity ¹⁰
Nutritional / Metabolic	Liver Abscesses	Polymicrobial infection following rumen insult	Decreased ADG, worse G:F, reduced carcass weight ¹¹
Nutritional / Metabolic	Fescue toxicosis	Endophyte (<i>Epichloë coenophiala</i>)–derived ergot alkaloids	Reduced feed intake, reduced ADG, impaired thermoregulation, increased DOF ¹²
Infectious (non-respiratory)	Pinkeye (IBK)	<i>Moraxella bovis</i> , <i>Moraxella bovoculi</i>	Reduced ADG ¹³
Infectious (non-respiratory)	Anaplasmosis	<i>Anaplasma marginale</i>	Weight loss, reduced weight gain, anemia, increased mortality in severe cases ¹⁴
Non-infectious / Environmental	Heat Stress	Elevated ambient temperature, humidity, solar radiation; high temperature–humidity index (THI)	Reduced feed intake, reduced ADG, reduced feed efficiency, increased DOF ¹⁵
*ADG = average daily gain; DOF = days on feed; F:G = feed-to-gain ratio; GI = gastrointestinal; IBK = infectious bovine keratoconjunctivitis; THI = temperature–humidity index. ¹Table 1; ²Step et al., 2002; Step and Smith, 2006; Fitzgerald and Mansfield, 1972; Sinks et al., 1992; ³Griffin, 1998; ⁴Tibbetts et al., 2006; ⁵Orsel et al., 2017; Holzhauer et al., 2018; Cortes et al., 2021; ⁶Fox et al., 1993; Fox et al., 2018; Stromberg and Gasbarre, 2006; ⁷Malone et al., 1982; Kaplan, 2001; Brown and Lawrence, 2010; Hayward et al., 2021; ⁸Johnson, 2006; Taylor et al., 2012; Burrow et al., 2019; ⁹Griffin, 1998; Step and Smith, 2006; ¹⁰Griffin, 1998; Nagaraja and Lechtenberg, 2007; ¹¹ Nagaraja and Lechtenberg, 2007; ¹²Parish et al., 2003; Aiken et al., 2007; McClanahan et al., 2008; Klotz et al., 2012, 2013; ¹³Step and Smith, 2006; ¹⁴ Kocan et al., 2003; Aubry and Geale, 2011; ¹⁵Hahn, 1999; Mitlohner et al., 2001			

Table 5.2. Reported impacts of morbidity and treatment frequency on feedlot cattle performance and carcass characteristics.

Disease	Treatments, n	ADG, kg/day	change from 0 treatments (%)*	FBW, kg	change from 0 treatments (%)*	HCW, lb	change from 0 treatments (%)*	Reference
Bovine respiratory disease	0	1.29		537		343		Holland et al., 2010
	1	1.26	-2.33	532	-0.93	337	-1.75	Holland et al., 2010
	2	1.26	-2.33	527	-1.86	334	-2.62	Holland et al., 2010
	3	1.18	-8.53	535	-0.37	338	-1.46	Holland et al., 2010
	Chronically Ill	1.06		506		312		
			-17.83		-5.77		-9.04	Holland et al., 2010
	0	1.41				372		Wilson et al., 2016
	1	1.51	7.09			369	-0.81	Wilson et al., 2016
	2	1.43	1.42			360	-3.23	Wilson et al., 2016
	≥ 3	1.54	9.22			353	-5.11	Wilson et al., 2016
	0	1.42				343		Brooks et al., 2011
	1	1.39	-2.11			337	-1.71	Brooks et al., 2011
	2	1.37	-3.52			333	-3.04	Brooks et al., 2011
	3	1.31	-7.75			339	-1.20	Brooks et al., 2011
	Chronically Ill	1.19				320		
			-16.20				-6.83	Brooks et al., 2011
	0	1.80		635		348		Blakebrough-Hall et al., 2020
	1	1.70	-5.56	626	-1.43	344	-1.01	Blakebrough-Hall et al., 2020
	2	1.30	-27.78	582	-8.37	321	-7.85	Blakebrough-Hall et al., 2020
	≥ 3	1.10	-38.89	560	-11.69	308	-11.38	Blakebrough-Hall et al., 2020
	0	1.81		559		348		Montgomery et al., 2009
	1	1.78	-1.66	552	-1.25	350	0.57	Montgomery et al., 2009
	2	1.74	-3.87	539	-3.58	343	-1.44	Montgomery et al., 2009
	3	1.75	-3.31	536	-4.11	341	-2.01	Montgomery et al., 2009
	0	1.47				341		Cernicchiaro et al., 2013
	1	1.36	-7.48			336	-1.34	Cernicchiaro et al., 2013
	2	1.30	-11.56			335	-1.68	Cernicchiaro et al., 2013

	1.24				330		Cernicchiaro et al., 2013
≥ 3		-15.65				-3.33	
0	1.53		523		332		Gardner et al., 1999
1	1.49	-2.61	513	-1.97	327	-1.69	Gardner et al., 1999
≥ 2	1.35	-11.76	498	-2.92	312	-6.14	Gardner et al., 1999
0	1.79		598		377		Thomson et al., 2012
1	1.68	-6.09	588	-1.67	372	-1.32	Thomson et al., 2012
≥ 2	1.58	-11.68	578	-3.34	367	-2.64	Thomson et al., 2012
0	1.46		556				Faber et al., 1996
1	1.47	0.62	557	0.08			Faber et al., 1996
2	1.50	2.48	558	0.33			Faber et al., 1996
≥ 3	1.43	-1.86	541	-2.69			Faber et al., 1996
0	1.49		509		314		Reinhardt et al., 2009
1	1.27	-14.77	503	-1.32	309	-1.37	Reinhardt et al., 2009
≥ 2	1.09	-26.85	501	-1.53	307	-2.20	Reinhardt et al., 2009
0	1.44		531		323		Schneider et al., 2009
≥ 1	1.37	-4.86	520	-2.07	315	-2.48	Schneider et al., 2009
0	1.77		327				Picket et al., 2023
1	1.61	-9.04	312	-4.59			Picket et al., 2023
≥ 2	1.51	-14.69	308	-5.81			Picket et al., 2023
0	1.00				337		Snowder et al., 2007
≥ 1	1.02	2.00			330	-2.08	Snowder et al., 2007
0					371		Garcia et al., 2009
≥ 1					368	-0.92	Garcia et al., 2009
0					342		Garcia et al., 2009
≥ 1					337	-1.54	Garcia et al., 2009
All morbidities							
0	1.51		557		310		Jim et al., 1993
≥ 1	1.54	1.99	562	0.92	311	0.45	Jim et al., 1993
0	1.63		554		354		Roeber et al., 2001
1	1.69	3.68	564	1.64	357	1.02	Roeber et al., 2001
2	1.63	0.00	546	-1.51	345	-2.60	Roeber et al., 2001
0	1.64		577		372		Hands et al., 2012
1	1.67	1.83	586	1.56	378	1.61	Hands et al., 2012
2	1.48	-9.76	564	-2.25	365	-1.88	Hands et al., 2012
≥ 3	1.48	-9.76	557	-3.47	360	-3.23	Hands et al., 2012
0	1.45		542		347		Parish et al., 2012
1	1.49	2.76	549	1.29	349	0.58	Parish et al., 2012
≥ 2	1.39	-4.14	536	-1.11	340	-2.02	Parish et al., 2012
0	0.64		244		155		Gadberry and Troxel, 2006
≥ 1	0.61		241		151		Gadberry and Troxel, 2006
		-4.26		-1.30		-2.63	
0	1.44				353		Waggoner et al., 2007
1	1.36	-5.56			348	-1.42	Waggoner et al., 2007

≥ 2	1.24	-13.89	763	-1.98	Waggoner et al., 2007
0			317		Bloomberg et al., 2013
1			309	-2.49	Bloomberg et al., 2013
≥ 2			316	-0.09	Bloomberg et al., 2013

Table 5.3. Model-adjusted means (standard error of the means) for calculated estimates of carbon dioxide equivalent (CO₂e) emissions from the production of heifers that received one of three different bovine respiratory disease (BRD) control programs and were monitored by one of two disease detection strategies.

Parameter	BRD Control Strategy ¹				Disease Detection Strategy ²			BRD Control Strategy x Disease Detection Strategy
	NC	PC	TBCP	<i>P</i> -value	PR	ADD	<i>P</i> -value	<i>P</i> -value
Feedlot finishing footprint, kg CO ₂ e ³								
per kg final BW	1.58 (0.03)	1.54 (0.03)	1.59 (0.03)	0.23	1.57 (0.02)	1.53 (0.02)	0.01	0.86
per kg HCW	2.52 (0.05)	2.44 (0.05)	2.52 (0.05)	0.16	2.50 (0.04)	2.44 (0.04)	0.02	0.78

¹Three BRD control strategies were evaluated: Negative Control (NC), Positive Control (PC; 100% of treatment group received the BRD control antimicrobial which reflects traditional management), or a Targeted BRD Control Program (TBCP; individual animal prediction of BRD risk generated by a novel hardware/software system capturing cardiopulmonary data subsequently analyzed by machine learning techniques).

²Two disease detection methods were evaluated: an automated disease detection system (ADD; a novel hardware/software system designed to continuously capture animal temperature and activity and whose data is analyzed by machine learning techniques) and traditional pen riding (PR) practices which reflect conventional management.

³Sum of estimated CO₂e generated during the finishing period from feedlot operations, manure, and enteric methane.

Chapter 6 - Conclusions

This dissertation evaluates sustainability in the beef industry as an outcomes-based, production-relevant concept, recognizing that sustainability in feedlot systems must be assessed using metrics that align with stakeholder and producer decision-making. To address this challenge, a combination of experimental trials, observational research, and systems-based modeling approaches was employed to examine interrelated questions at the intersection of cattle health, production efficiency, and environmental sustainability within U.S. feedlot systems. This work is grounded in the premise that animal health is integral to sustainability, as it directly influences production efficiency and environmental performance. Health, performance, and emissions intensity (EI) are therefore evaluated as tightly linked components of a single production system, using commercial-scale data and decision-relevant metrics that reflect real-world conditions. This integrated framework provides the foundation for synthesizing the collective findings of the dissertation and evaluating their implications for sustainable beef production.

Sustainability in feedlots is fundamentally efficiency-driven

In feedlot systems, environmental outcomes are closely tied to production efficiency, as cattle that grow faster and utilize feed more effectively require fewer resources per unit of beef produced. Lubabegron was the first feed additive approved by the U.S. Food and Drug Administration for reducing gas emissions from feedlot cattle. In Chapter 2, a large-pen commercial feedlot trial compared Exuperior (EXP) with Optaflexx (OPT), a commonly used beta-adrenergic agonist, in crossbred beef steers. Cattle fed EXP exhibited improved growth performance and feed efficiency, accompanied by reduced dry matter intake and heavier

carcasses, as compared to cattle fed OPT. These performance improvements translated to a 6.2% reduction in estimated carbon dioxide equivalents emissions per unit of carcass weight and higher estimated net returns per animal shipped relative to OPT. Collectively, these findings demonstrate that the environmental benefits associated with EXP were achieved through improvements in growth rate and feed utilization, illustrating that EI decreases when cattle grow faster and convert feed more efficiently.

Understanding how routinely collected health and production metrics in commercial feedlot systems translate to environmental outcomes is critical for meeting both sustainability objectives and global protein demands. In Chapter 3, observational data from U.S. commercial feedlots were used to quantify associations among average daily gain (ADG), feed efficiency (G:F), disease burden, mortality, and estimated EI. Across diverse production conditions, cattle with higher ADG and improved G:F consistently exhibited lower EI, although the magnitude of these relationships varied by sex and season, reflecting biological and management variability inherent to commercial systems. These findings demonstrate that emissions outcomes are not uniform across cattle populations but are strongly shaped by production conditions and performance variability commonly encountered in commercial systems. By linking routine performance and health metrics to EI, this work provides a practical framework for implementing targeted, efficiency-based strategies that support both sustainability objectives and protein production goals.

Chapter 5 synthesized findings from the preceding chapters to clarify the mechanisms through which production efficiency shapes EI in beef production systems. This integrated analysis demonstrated that cattle growth rate and feed utilization are direct determinants of EI, as animals that convert inputs into body weight more efficiently require fewer resources per unit of

beef produced. Factors that disrupt efficient growth, including health challenges, were shown to extend days on feed and increase EI, presumably by elevating maintenance requirements relative to productive output. Collectively, these findings emphasize that strategies aimed at improving growth performance and feed utilization represent effective pathways for reducing EI while simultaneously supporting productivity.

Animal health is essential for sustainable beef production

Animal health functions as a fundamental production-limiting factor in feedlot systems, with direct implications for EI and environmental sustainability. In Chapter 3, observational research using commercial feedlot data demonstrated that increased disease burden and mortality were consistently associated with higher EI. For example, reducing mortality from 5% to 0% was estimated to lower lifetime EI by nearly 6%, reflecting the recovery of productive output from resources already invested. However, the magnitude of health-related effects on EI varied substantially by season and by cattle weight at feedlot arrival, with the greatest impacts observed in lighter-weight cattle and during specific seasons. This heterogeneity underscores that health-related sustainability outcomes are strongly context-dependent within commercial production systems. From a sustainability perspective, mortality results in a complete loss of resources invested in animal maintenance and growth, with important implications for EI (Capper, 2020). Importantly, health remains a sustainability issue even when animals survive, as morbidity can reduce feed intake, slow growth, increase days on feed, and introduce greater performance variability, collectively impairing feed efficiency, carcass value, and EI across feedlot systems (Capper, 2020).

Chapter 4 further clarified the role of animal health management in sustainability by demonstrating that the effects of bovine respiratory disease (BRD) treatment decisions are highly

context-dependent. This study compared tulathromycin, tulathromycin + ketoprofen, and tildipirosin for first treatment of naturally occurring BRD in a commercial feedlot setting. Across all treatment groups, no differences were observed in morbidity, retreatment risk, or mortality at 60 days, 100 days, or through closeout. Under the conditions evaluated, these macrolide-based treatment options had limited influence on BRD outcomes in medium-risk feedlot cattle. These findings indicate that, within this risk class and management context, treatment selection among comparable products did not meaningfully alter downstream health or performance outcomes. From a sustainability perspective, this highlights the importance of aligning health interventions with cattle risk profiles and production context, as the sustainability impacts of disease management decisions depend on how effectively they reduce disease burden and associated performance losses within a given system.

Chapter 5 integrated findings from across the dissertation to demonstrate how animal health fundamentally shapes sustainability outcomes in beef production systems. This synthesis shows that BRD and other common health challenges compromise feedlot efficiency and increase EI, reinforcing the critical role of cattle health in sustainable beef production. Poor health and mortality further exacerbate EI by wasting resources invested in animals that fail to reach harvest, resulting in no productive return on those inputs. Collectively, these findings illustrate that strategies aimed at improving cattle health and growth efficiency represent effective and scalable pathways for reducing EI while simultaneously supporting productivity and animal welfare. Keeping cattle healthy is therefore not only an ethical imperative, but a biological and environmental necessity for sustainable beef production.

Implications for the scientific community

The findings of this dissertation demonstrate the value of integrating epidemiological methods, production performance metrics, and environmental modeling to evaluate sustainability in livestock systems. By linking animal health, growth performance, and EI using commercial-scale data, this work illustrates how population-level variation and real-world production conditions shape sustainability outcomes. Studies that evaluate environmental impacts in isolation, without accounting for morbidity, mortality, or performance variability, risk producing incomplete or misleading conclusions. The results presented here highlight that animal health is a critical determinant of production efficiency and EI, therefore must be explicitly incorporated into sustainability assessments. Collectively, this work reinforces the need for systems-based, population-level analyses that reflect the complexity of commercial beef production rather than relying on average-animal assumptions or narrowly defined environmental metrics.

Implications for the beef industry

For the beef industry, the results of this dissertation provide evidence that many existing best practices already support sustainability objectives when evaluated using appropriate, production-relevant metrics. Across multiple analyses, improvements in animal health, growth performance, and feed utilization were consistently associated with lower EI, reinforcing the alignment between economic performance and environmental outcomes in feedlot systems. The emphasis on EI, rather than total emissions, supports sustainability metrics that are compatible with commercial decision-making and routinely collected production data. Findings from this work further indicate that the sustainability impacts of management and intervention decisions are highly context-dependent, varying with cattle risk profiles, production conditions, and management consistency. As a result, sustainability gains in feedlot systems are most effectively

achieved by optimizing core production and health management practices within a given context, rather than by relying on narrowly defined or stand-alone environmental solutions.

Implications for sustainability communication

This dissertation also has important implications for how sustainability in beef production is communicated to broader audiences. By explicitly linking animal health and production efficiency to EI, this work challenges narratives that portray animal health and environmental responsibility as competing or independent objectives. The findings provide a defensible, data-driven framework for sustainability claims that reflects both biological realities and commercial production constraints. Importantly, this approach helps bridge the gap between producer experiences and the expectations of corporate, policy, and consumer stakeholders by demonstrating that improvements in animal health and production efficiency can simultaneously support environmental, economic, and animal welfare outcomes. Clear communication of these relationships may enhance transparency and trust in sustainability assessments while promoting more informed and constructive discussions about livestock production systems.

Limitations and context for interpretation

The findings of this dissertation should be interpreted within the context of several overarching limitations. Greenhouse gas emissions were estimated using established modeling frameworks rather than directly measured, which introduces uncertainty inherent to any modeling approach. However, the use of EI and production-relevant inputs helps ensure that estimates remain comparable and decision-relevant across commercial systems. Additionally, all analyses were grounded in data from U.S. commercial feedlot production systems, and results may not be directly generalizable to alternative production systems or geographic regions with different management practices or resource constraints. Finally, some effects, particularly product-level

differences among comparable interventions, may be small or context-dependent and therefore difficult to detect consistently across populations. These limitations do not detract from the conclusions of this work but rather provide appropriate context for interpreting the results and applying them within relevant production settings.

Future directions for sustainable beef production research

The findings of this dissertation highlight several important opportunities for future research to further advance sustainability assessment in beef production systems. Integrating lifetime greenhouse gas emissions across multiple production phases, from cow-calf through feedlot finishing, would provide a more comprehensive understanding of how health and performance interventions influence environmental outcomes over the full production cycle. Additional work is also needed to better characterize the impacts of morbidity severity and subclinical disease, which may exert meaningful effects on productivity and EI despite being difficult to quantify using conventional health records. Future research also could benefit from approaches that evaluate profitability and emissions outcomes together, reflecting how producers make real-world decisions. Finally, additional research evaluating prevention strategies that reduce disease burden and associated performance losses in commercial feedlot systems may help identify the most effective opportunities to improve animal health, productivity, and sustainability simultaneously.

Concluding synthesis

This dissertation demonstrates that sustainability in beef production is closely linked to how efficiently cattle convert resources into productive output within biologically and economically viable systems. Across multiple study designs and analytical approaches, animal health emerged as a central determinant of production efficiency and EI, linking ethical,

economic, and environmental dimensions of sustainability. Healthier cattle grow more efficiently, require fewer resources per unit of beef produced, and generate lower EI, reinforcing the alignment between animal well-being and environmental performance. By integrating animal health, production metrics, and emissions modeling using commercial-scale data, this work provides a pragmatic and defensible framework for evaluating sustainability in feedlot systems. Collectively, these findings support the conclusion that healthier cattle are not only more productive, but also more sustainable, and that meaningful progress in beef sustainability will depend on continued emphasis on health, efficiency, and systems-based decision-making.

References

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