

Evidence-based approaches to health risk mitigation and value creation in U.S. livestock
production systems

by

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D.V.M., Universidade Federal Fluminense, 2017
M.S., Kansas State University, 2020

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Diagnostic Medicine and Pathobiology
College of Veterinary Medicine

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2025

Abstract

The U.S. livestock industry faces increasing pressure to balance productivity, economic efficiency, and sustainability while minimizing disease risks, antimicrobial use, environmental impacts, and animal welfare concerns. This dissertation applies epidemiological and economic principles to enhance evidence-based decision-making for managing agricultural risks across diverse livestock systems. Agricultural risks are commonly categorized as financial, institutional, human resources, market, and production risks. Yet, effective management goes beyond objective classifications; it also requires an understanding of how producers and other stakeholders perceive and interpret these risks. Perceptions shape how risks are prioritized, and which management strategies are adopted, influencing outcomes at both the farm and industry levels. Outcomes research provides a framework for integrating scientific evidence with practical decision-making in livestock systems. By applying clinical and population-based methods to evaluate the effectiveness and value of interventions, it bridges the gap between research and practice, reduces uncertainty, and strengthens the producers' capacity to manage agricultural risks through informed, evidence-based strategies. These concepts are described and discussed in Chapter 1.

Chapter 2 is a rapid systematic review synthesizing knowledge on the role of swine in the transmission dynamics of Japanese encephalitis virus (JEV), diagnostic methods, and preventive and surveillance strategies. The review highlights key data gaps in the potential role of feral swine in JEV transmission, identifying priorities for U.S. surveillance and preparedness to mitigate the risk of JEV introduction and establishment. A survey design was employed in Chapter 3 to characterize veterinarian and feedlot manager perceptions and decision-making considerations regarding metaphylaxis use for cattle at moderate risk of bovine respiratory

disease. The study identifies both alignment and divergence in how disease risk, information access, and management priorities influence antimicrobial use, underscoring opportunities to improve communication and support antimicrobial stewardship within feedlot systems. In Chapter 4, observational auction market data were used to evaluate the economic impact of value-added management programs on feeder calf sale prices. Through regression modeling, the study estimates price premiums associated with specific program combinations and illustrates how information asymmetries may influence market efficiency and producer decision-making capacity.

Together, these studies emphasize the central role of information — derived from diverse data sources and research approaches — in improving disease risk management and supporting sustainable livestock production. With them, the need for continued investment in data integration, traceability systems, and communication frameworks that enhance transparency (or information access) and evidence-based practice is highlighted. Strengthening information networks will be essential for improving efficiency and profitability, adapting to evolving societal values, and ultimately promoting the resilience of U.S. livestock systems.

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Acknowledgements

As I reach the end of this journey, I am filled with gratitude for the many individuals who have supported and guided me along the way. First, I thank my advisor, Dr. Natalia Cernicchiaro, for her mentorship, intellectual generosity, dedication, and patience. It has been a journey, and I am truly grateful for the opportunity to join Dr. Cernicchiaro's group and the Center for Outcomes Research and Epidemiology, a team of exceptionally knowledgeable and dedicated professionals whose high standards and commitment to excellence have profoundly shaped my growth as both a researcher and an individual. I am also grateful to my committee members, Dr. David Renter, Dr. Andrea Dixon, and Dr. Glynn Tonsor for their mentorship within their respective disciplines and for their support throughout the pursuit of this degree. I have learned immensely from each of them, whether through coursework, research discussion, or project collaborations. I would also like to extend my gratitude to Dr. Christy Hanthorn, who, despite having no formal obligation to assist in my research, was equally dedicated and contributed meaningfully to my work. My sincere thanks also go to Ashley Thackrah, Dr. T.G. Nagaraja, Dr. Adryanna Siqueira Drake, Dr. Mike Sanderson, Taylor McAtee, Torre Dunlea, Stephen Edache, David Edache, and Barb Turner for their steady support, valuable insights, and encouragement throughout my doctoral studies. It has been an honor to be part of such a tremendous working group.

Lastly, I would like to express my deepest gratitude to my family for their endless love and support throughout this journey. To my parents, thank you for instilling in me resilience and the determination to pursue my goals, no matter the challenges, and for teaching me the value of hard work, integrity, and perseverance. To my pets, Loki, Meow Meow II, Leo, and Indi, thank you for keeping our home a sanctuary, filling it with joy, laughter, and for always reminding us

of what truly matters. To my husband, best friend, and colleague, Dr. Lucas Horton, thank you for your unwavering support and belief in me, even during the most difficult moments, and for walking beside me through every long night and demanding day. Your love and encouragement have been my greatest sources of strength. I am so proud of us and so grateful to have shared this journey with you.

Preface

Chapters 2 through 4 of this dissertation are formatted according to the respective journal guidelines in which they were published or are intended to be published. Tables and Figures were renumbered for logical sequence and to fit the dissertation format; otherwise, the content remains unchanged from the original publications.

Chapter 1 - Introduction

Livestock producers routinely face decisions that directly affect both the health of their animals and the economic sustainability of their operations. This dissertation examines agricultural risks across different livestock species and production systems, focusing on how stakeholders respond to those risks through management strategies informed by available evidence on their benefits, impacts, and costs. This overarching theme underlies the studies described in the following chapters of this dissertation.

Weighing risks and benefits in agricultural management strategies

Effective disease prevention and risk mitigation are essential to sustainable livestock production, but their adoption depends on carefully balancing perceived risks, costs, and anticipated benefits, such as trust in intervention outcomes and potential value added to the final product. These trade-offs include decisions on whether to, or how much to invest in disease prevention (balancing true and perceived risks of endemic vs. emerging diseases against costs), adopt specific management practices (weighing public perception and animal welfare against production impacts and return on investment), and pursue certification programs that imply higher sale prices (evaluating potential premiums relative to investment).

Risk and uncertainty

The concept of “risk” encompasses a range of interpretations but is often associated with uncertainty in the outcome of an action or event and the potential for consequences that affect “something of value” (Harwood, et al., 1999; Hardaker, 2015; Gluckman, 2016). More specifically, risk has been described as a function of the likelihood of an event occurrence and the consequence (or cost) of exposing something of value to a hazard (Dall, 2010; Gluckman, 2016). Hazards to something of value may involve the probability of losing money,

repercussions that affect other resources, harm to health, and other types of events that affect a person's welfare (Harwood, et al., 1999). The magnitude of the risk is influenced by the level or frequency of exposure, the vulnerability of the asset(s) (i.e., thing(s) of value), the characteristics of the hazard, and how likely an event is to occur (Gluckman, 2016). Additionally, while "risk" can be described in objective terms, the perception of risk is a product of subjective judgements of likelihood and impact, shaped by particular values and experiences, which inevitably varies considerably from individual to individual.

Agricultural risk

Agricultural activities are inherently risky. Because agricultural production often occurs over large areas with limited control over environmental and weather conditions and involves the management of living plants and animals, risk arises from multiple sources and is experienced differently across geographic regions and socioeconomic contexts. Agricultural risks have been classified into five general types: financial, institutional (or legal), personal (or human resources), market, and production risks (Boehlje and Trede, 1977; Baquet 1997; Harwood, et al., 1999; Duong et al., 2019; Komarek et al., 2020). These risks are considered interrelated and may amplify one another.

Financial risk arises from the additional variability in cash flow of the operation resulting from fixed financial obligations associated with debt financing and cash leasing (Gabriel and Baker, 1980). Shifts in interest rates, changes in credit availability, or tighter loan conditions can all increase financial vulnerability (Gabriel and Baker, 1980). Institutional risk results from uncertainties related to policy and regulations that affect agriculture (Harwood et al., 1999). Changes in international trade agreements, environmental regulations, animal welfare requirements, taxation, currency fluctuations, and (or) other evolving policy and regulatory

frameworks (often shaped by broader political dynamics) can reshape market access to essential inputs for production and to markets for selling outputs (Harwood et al., 1999). Human resources (or personal) risks, such as injuries or death from farm machinery or other farm hazards, adverse health effects from pesticide or dust exposure, or zoonotic disease transmission between livestock and humans, directly affect production and decision-making capacity, and thus the long-term viability of the farm business (Hardaker et al., 2015).

Although these (beforementioned) agricultural risks are important, the research presented in the following chapters of this dissertation focuses more directly on production and market risks, particularly those associated with disease management and value-added marketing strategies. Market risk involves uncertainty regarding future prices, costs, and market access, which may occur after the commitment to production has begun. Potential losses arise from output and input price fluctuation, market shocks, and shifts in demand (Harwood et al., 1999). Price volatility in agricultural commodities can be driven by weather events (e.g., droughts, floods), pest or disease outbreaks and their effects on yields (or gain efficiency), and fluctuations in inputs (e.g., fertilizer, energy, fuel prices) that directly influence production costs (Komarek et al., 2020). Livestock production systems are particularly vulnerable given the need for ongoing investments in feed, animals, products related to management strategies, and equipment that may not generate returns until months or years later. Moreover, because markets are highly interconnected, producer returns may be heavily influenced by events occurring far beyond the local or even national level (Harwood et al., 1999). In addition to these market dynamics, information asymmetries can further amplify market risk by creating unequal access to price or demand signals (Perloff and Rausser, 1983). Larger companies often have the resources and access to large databases that allow them to monitor market trends and adjust strategies

accordingly, whereas individual producers may lack access to such information. This misalignment reduces the efficiency with which supply responds to demand, and contributes to uneven decision-making capacity across market participants, with larger market players (or those with privileged access to information) being better positioned to adapt and act on unshared market information than smaller producers. For example, a producer who learns of increased market demands for non-hormone-treated cattle (NHTC) may attempt to source them, but if other local producers have already used hormonal implants in their calves due to a lack of access to similar information, the supply becomes limited and the opportunity is delayed or lost.

Beyond market-related uncertainties, producers face substantial production risk, which arises from uncertainty in biological and natural processes in crop and livestock systems (Komarek et al., 2020). Production outputs are affected by weather events (e.g., excessive or insufficient heat, cold, or rainfall), pest and disease outbreaks, and environmental factors such as soil or water contamination, all of which are largely beyond the producer's control. Similar to market risk, effective information access and utilization can help minimize production risk.

Research contributes to minimizing production risk by addressing key knowledge gaps and generating evidence through various study designs focused on pathological mechanisms, risk factors, and preventive strategies for disease threats. Rapid systematic literature reviews of emerging animal health issues, for instance, can provide timely and practical guidance for producers to adapt management strategies and safeguard operations. In addition, tools that integrate operational data with predictive modeling approaches offer producers a means to reduce uncertainty and guide decision-making by aligning information generation with their management needs.

Risk perception

A comprehensive understanding of risk goes beyond objective definitions and classifications; it also requires understanding how producers, and other stakeholders perceive and interpret these risks. Risk perception is the subjective element that explains why certain risk management strategies are adopted, or not, by producers. Perceptions shape the importance producers assign to different risks and their respective management strategies, which ultimately influence their implementation choices (Renn, 1989). This perspective not only provides essential context for interpreting behavioral observations of a particular population (e.g., survey results on which technologies are being adopted and which are not) but also helps to guide subsequent research by identifying which strategies matter most to that population and therefore are most likely to be adopted and prioritized.

Producers' risk management responses are shaped by their risk perceptions, specifically whether they believe the implementation of an intervention or behavioral change justifies the required investment of money, time, and the psychological effort to alter established habits (Mankad 2016). Wachinger et al. (2013) defined risk perception as the way individuals relate to, collect, select, and interpret signals about uncertain impacts of events, activities, or technologies. Building on this understanding, Osiemo et al. (2021) proposed a framework in which risk perceptions are influenced by three broad factors: individual characteristics, risk attributes, and trust in communicating institutions.

Individual characteristics include factors such as age, gender, education, culture, religion, personal experience, and wealth, all of which correlate with different risk perceptions that drive distinct economic behaviors and decision-making, including response to risk (Wachinger et al., 2013; Sullivan-Wiley et al., 2017; Duong et al., 2019). Risk attributes consider the characteristics of a risk that influence an individual's intuitive judgement of the risk, such as its frequency,

probability, consequences, severity, sources, and the ability to control, prevent or adapt (Renn, 1989; Osiemo et al., 2021). Such an assessment will depend on how clear the various risks and their attributes are understood by the individual. Trust in communicating institutions refers to the extent in which individuals consider the source of information about a risk credible and reliable, which in turn determines whether they accept and act upon such information. Wachinger et al. (2013) reviewed the literature and concluded that trust (or lack thereof) in authorities, protective agencies, and experts, along with personal experience, is a primary factor shaping risk perceptions of natural hazards, particularly by influencing whether an individual's understanding of risk translates into action.

Moreover, producer-level choices to adopt management strategies and successfully manage risks are shaped by complex relationships between the actual presence of risk (exposure) and how these risks are perceived by producers. Outcomes research, defined as the application of clinical- and population-based research methods to optimize the effectiveness and value of interventions to stakeholders (Jefford et al., 2003; Cernicchiaro et al., 2022), offers an avenue to improve our understanding of risk exposure and the effectiveness of practical management strategies. By doing so, it helps reduce uncertainty, supports informed decision-making, guides policy and institutional support, and ultimately strengthens agriculture resilience by enhancing the producers' capacity to manage risk.

Risk management strategies

Managing production risk is central to agriculture resilience, as these uncertainties directly influence both the quantity and quality of outputs (Duong et al., 2019). Numerous risk management strategies have been proposed, identified, and (or) developed to support the long-term sustainability of agricultural business (Boehlje and Trede, 1977; Hardaker et al., 2015;

Harwood et al., 1999; Duong et al., 2019). However, because risk exposure, perception, and the tolerance to bear risks vary across producers and operations, the risk management strategies employed also differ. Most producers use a combination of strategies and tools to manage risks (Kahan, 2008). Certain strategies target a single type of risk, whereas others address multiple risks simultaneously. Different risk management strategies in agriculture have been classified into general categories, including financial, human, institutional, marketing, and production (Boehlje and Trede, 1977; Kahan, 2008).

Financial risk management strategies, as the name suggests, reduce financial risk by supporting the overall financial health and stability of a farm business. According to Baquet (1997), effective management of financial risk relies on sound financial planning and control through continuous monitoring of a farm's capacity to bear financial risk. Financial statements, such as balance sheets, owner equity, income, and cash flow are central to this process, as they provide the basis for tracking financial position, controlling expenditures, and evaluating the financial performance of the business (Baquet, 1997). The main financial risk factors for a farm relate to liquidity, solvency, profitability and repayment capacity, which are incorporated into financial ratios to provide producers with a standardized framework for assessing financial performance and overall business health (Crane et al., 2013).

Human risk management strategies help protect producers from risks associated with human resources which encompasses unexpected changes in labor availability and productivity. Hiring workers with appropriate skills and experience, establishing lawful and fair employment arrangements with competitive wages and safe working conditions, and ensuring regular communication, supervision and training were described as ways of providing adequate human resources management to reduce risk of unexpected labor shortages (Kahan, 2008). In addition,

careful labor planning, such as the use of a seasonal labor calendar, can help producers anticipate labor needs at different productivity stages of the production cycle (Kahan, 2008). One way large producers address labor productivity risks is by shifting from hand labor to animal power, tractors, or mechanized equipment (Kahan, 2008).

Institutional risk management strategies in agriculture involve utilizing formal structures, such as social or contractual arrangements, producer groups, cooperatives, government programs, and insurance, to prevent or mitigate the impacts of unpredictable changes in the provision of services and information, contractual arrangements, and (or) in government policies that affect farming (Kahan, 2008). Producer groups can serve as valuable resources of information for their members, providing updates on financing opportunities, regulatory and policy changes, expected market prices and input costs, and the quality of inputs and final products. These groups can also contract advisory services, such as legal counsel, on behalf of all members – maximizing the value of the service by spreading costs and ensuring broader access. As noted by Baquet (1997), legal expertise is often essential for drafting contractual arrangements, restructuring business organizations, planning generational transitions, and (or) resolving disputes. Participation in formal cooperative organizations further enables producers to benefit from collective actions such as volume sales of outputs, bulk purchasing of inputs, and improved access to credit. By organizing collectively, producers also strengthen their negotiating power with buyers, traders, and government entities.

Marketing risk management strategies include proactive measures intended to reduce the producers' exposure to price variability and uncertainty in future markets, thereby improving the predictability of returns. Diversification, such as planting multiple crops or integrating livestock (Heady 1952; Boehlje and Trede, 1977; Hardaker et al., 2015), hedging with financial

instruments like futures and options to prices (Goodwin and Schroeder, 1994; Boehlje and Trede, 1977), using marketing and forward contracts to establish prices and sales terms with buyers (Goodwin and Schroeder, 1994; Banquet 1997), spreading sales throughout the year (Boehlje and Trede, 1977), and obtaining insurance (Hardaker et al., 2015) to safeguard against market price volatility or production losses, are some examples of marketing risk management strategies.

Price variability is among the most significant risks faced by agricultural producers (Goodwin and Schroeder, 1994). For example, beef cattle producers have ranked cattle price fluctuations as one of the top risk factors affecting their operations (Hall et al., 2003). In recognition of the significant price risks faced by livestock producers, the Agricultural Risk Protection Act of 2000 expanded the federal crop insurance program to include livestock. Under this framework, the U.S. Department of Agriculture's Risk Management Agency offers various insurance program options to farmers, including Livestock Risk Protection, which protects producers against unexpected price declines in future markets, and Livestock Gross Margin, which insures the margin between input costs (such as feed) and the market value of livestock. Together, these programs aim to reduce producers' exposure to price volatility and help stabilize farm revenues.

In addition to market risk, producers also face significant production risks. Production risk management strategies aim to mitigate the uncertainty surrounding the quantity and quality of outputs caused by unforeseen events such as adverse weather, disease outbreaks, or pest infestations. A wide range of strategies have been proposed to mitigate production risk, including the adoption of risk-reducing inputs and technologies, diversification of enterprises, geographic dispersion of production, maintaining system flexibility, engaging in off-farm income activities,

forward contracting, purchasing insurance, staying informed through continued education and data analysis, and developing contingency plans (Boehlje and Trede, 1977; Kahan, 2008; Crane, 2013). Technological approaches to reduce production risk include the use of disease-resistant livestock breeds, genetic improvements for productivity, enhanced pest and disease monitoring, and the utilization of crops and livestock management strategies that target improved marketability (Kahan, 2008, Crane, 2013; Njegomir et al., 2016; Duong et al., 2019). Ongoing agricultural research continues to advance these tools with the aim of improving production efficiency. Producers who remain engaged through education and data-driven decision-making are better positioned to identify and adopt emerging technologies. In particular, those who become early adopters may gain a competitive edge over later adopters. Practical examples of production risk management can also be observed in cattle markets, where calf management practices directly affect animal health and performance outcomes. For calf ranchers, adopting value-added management strategies such as source and age verification, preconditioning and weaning protocols, certification of Beef Quality Assurance or Global Animal Partnership programs serve as a production risk management approach by improving calf health status and overall marketability. At the same time, feedlot operators benefit by sourcing higher-quality, lower-risk calves, and therefore may be willing to pay a premium to reduce their own risks related to disease susceptibility, feedlot performance, carcass quality, and ultimately, meat product outcomes.

The role of information and research in managing agricultural risk

Above all, effective risk management depends on access to accurate information from reliable sources. Without sound information and continuous research, producers cannot evaluate strategies to mitigate diverse agricultural risks. Research also identifies knowledge gaps and

information needs for contemporary challenges while providing innovative solutions and up-to-date analyses that reduce uncertainty and guide the adjustment of agricultural practices over time. Moreover, by driving the development of new tools, technologies, and management practices, information serves as the foundation upon which all risk management strategies are built. Prior work has categorized agricultural information sources in a variety of ways (Jones, 1990; Kahan, 2008). I propose a modified grouping into three broad categories: operational (e.g., farm or internal records), institutional (data aggregated at the local-, industry-, or national-level), and research and innovation (external data).

Operational information (farm-level data)

Collecting and evaluating operational or internal (farm-level) data is essential for producers to effectively mitigate risks and strengthen the long-term viability of their operations. Farm-level data analysis provides individualized, evidence-based insights that account for the unique characteristics of each operation, enabling producers to identify inefficiencies, improve resource use, reduce costs, and enhance overall productivity within their specific production contexts. Advances in precision agriculture and precision livestock farming have greatly expanded producers' ability to collect, analyze, and translate these data into informed management decisions. Modern technological approaches rely on automated monitoring of individual animals, their environments, and behaviors to optimize health, growth, milk production, diseases detection, and overall welfare. Artificial intelligence and machine learning tools are increasingly being integrated into these systems to collect real-time data, identify patterns, and forecast potential risks.

By refining data collection and analysis, precision livestock farming enhances day-to-day management and empowers producers to move beyond assumptions or “gut feelings” towards

more proactive (i.e., early intervention), data-driven decision-making. Tailoring practices and inputs to the specific conditions of each operation enables producers to optimize returns, improve efficiency, and preserve natural resources, thereby strengthening the resilience and sustainability of their operations. Ultimately, the value of these approaches and operational-level data lies in delivering individualized insights that account for the unique characteristics of each operation.

Institutional information (group-level data)

Institutional information and policies play a complementary role to farm-level data in guiding agricultural risk management within regions or groups of producers governed (or influenced) by a common entity or regulatory body (e.g., countries, states, counties, cooperatives, suppliers). While operational records capture the internal dynamics of a specific operation; policies, regulations, market summaries, industry reports, and institutional programs provide external reference points that shape decision-making and influence the long-term sustainability of operations within their broader context. Such information often originates from aggregated data at the group level or from scientific reports deemed relevant to that particular group of producers, and disseminated by group-level leadership, such as government agencies, extension services, producer or industry organizations, and certification programs. Together, these entities translate broader societal, economic, and scientific priorities into actionable guidance for producers who share the same socio-political environment.

A key function of institutional information is to reduce uncertainty by setting clear expectations and providing structured decision-support resources for groups of producers with shared values and (or) goals. Policy frameworks act, not only, as regulatory structures but, also, as information pipelines, connecting producers to validated research and collective data sources. For example, federal and state programs related to biosecurity, animal health surveillance, or

environmental conservation, not only, establish compliance requirements but, also, disseminate research-based standards and best practices, and direct research priorities to safeguard agricultural production at that level. Similarly, certification programs and value-added initiatives communicate market signals that help producers weigh the risks and rewards of adopting new practices.

Furthermore, policy and institutional information provide a broader framework for risk management that complements the insights generated at the farm level. By transforming scientific research into guidelines, monitoring systems, and decision-support tools, institutions help producers reduce risk, enhance efficiency, and align their operational practices with evolving market, environmental, and regulatory conditions.

Research and novel information (external data)

Scientific studies serve as the primary source of knowledge creation, forming the foundation that enables information to be applied effectively to change and improve agricultural production systems at both the farm and institutional levels. Research generates insights that institutions translate into extension materials, risk management tools, and evidence-based recommendations, while also providing producers with novel insights that can be adopted as-is, or adapted, to the specific context of their operations to enhance efficiency and reduce exposure to production, market, and other agricultural risks. Research not only offers the primary or alternative solutions for agricultural challenges, inefficiencies, and risks, but also evaluates the effectiveness and impacts of adopting these strategies on various outcomes. For example, advanced analytics and simulation software developed by researchers allow governing bodies, institutions, and producers to model potential scenarios (e.g., natural disasters, feed shortages, disease outbreaks), evaluate mitigation strategies, and develop robust contingency plans that can

be implemented at multiple institutional levels. By generating generalizable knowledge and novel insights, research enables evidence-based use of information and interventions, promoting continuous improvement in agricultural practices. Such research-generated insights allow for adaptive decision-making at multiple levels, ensuring agricultural practices evolve with emerging knowledge to continue optimizing its productivity and sustainability.

There are multiple scientific methods available to address agricultural challenges, and the choice of approach depends on different considerations such as the research question, the type and strength of evidence needed (based on existing literature), available resources, and ethical constraints. Scientific processes are design to minimize bias and generate objective, valid evidence to support or refute a research hypothesis. While a single study can provide preliminary evidence and contribute to the broader body of knowledge, the strength of the evidence increases as multiple studies evaluate the same question (Sargeant et al., 2014). Under those considerations, different types of scientific evidence can be ranked according to their risk of bias, and therefore the strength (or the amount of confidence) one can have on the interpretation of results. Systematic reviews and Meta-analysis use rigorous, reproducible methods to synthesize evidence from multiple studies addressing the same research question, and are therefore generally considered the strongest source (or highest level) of evidence on a given research question (Clancy, 2002; Sargeant 2014). Conversely, expert opinions, editorials, and case reports offer weaker evidence due to their greater susceptibility to biases inherent to observational or anecdotal information (Sargeant et al., 2014). Nonetheless, most hypothesis testing typically begins with lower levels of evidence and progress toward more rigorous study designs, providing higher level of confidence in their findings, as support for a theory accumulates. In other words,

it is not possible to conduct a systematic review on a hypothesis that has never, or only rarely, been empirically evaluated.

In response to the potential threat of Japanese encephalitis virus (JEV) incursion into the U.S., the Swine Health Information Center proactively organized and supported research efforts to conduct a rapid systematic review to synthesize available evidence on the role of swine in JEV transmission (SHIC, 2023), with a focus on the U.S. context of swine production systems. Concern within the U.S. swine industry intensified after JEV expanded to mainland Australia in 2022, highlighting the urgent need to gather and evaluate relevant evidence to support timely preparedness measures for detection and containment of JEV in the event of its accidental introduction into the U.S. Endemic in Southeast Asia since the early 1900s, JEV is a complex vector-borne disease involving mosquito vectors, maintenance and amplifying hosts, and incidental hosts, including humans, who can develop clinical signs such as high fever and nausea, with severe cases potentially leading to death (Le Flohic and Gonzalez, 2011). As a result, a substantial body of literature has accumulated across diverse production system and socio-economic contexts from endemic countries. JEV-free countries can draw on this evidence not only to better understand disease dynamics and epidemiologic patterns, but also to inform preparedness and response strategies, identify knowledge gaps, and prioritize research efforts to strengthen their capacity to remain JEV-free.

A Rapid systematic review approach was used in Chapter 2 to synthesize current scientific knowledge on the role of swine in JEV transmission, reviewing animal- and environmental-related risk factors, diagnostic methods, preventive and surveillance strategies and identifying knowledge gaps that constrain evidence-based preparedness for U.S. swine producers and policymakers, thereby guiding research priorities to strengthen the U.S. response

capacity to this transboundary disease. Rapid systematic reviews are a streamlined version of systematic reviews that follow the same principles of evidence gathering and synthesis but are intended to deliver results more quickly. This approach is particularly valuable when timely information is essential and waiting for a traditional systematic review is not feasible. Rapid systematic reviews have emerged as an efficient tool for informing policymakers in urgent and (or) emerging public health contexts and are frequently used by national and international health agencies to inform guideline development and contingency plans (Garrity et al., 2017; Garrity et al., 2021).

The strength of evidence generated through synthesis methods ultimately depends on the quality and design of the primary studies included. Among these, randomized controlled trials typically provide the greatest internal validity but are often impractical or ethically challenging to implement in agricultural and economic settings. Observational studies, although more susceptible to biases, offer valuable insight under “real-world” conditions and allow for the evaluation of naturally occurring variation over time and across diverse populations. Descriptive studies, placed at the lowest level of the evidence hierarchy due to their high susceptibility to bias, are generally not included in systematic reviews, but can provide baseline or preliminary data that support hypothesis generation (Sargeant et al., 2014). The subsequent chapters apply descriptive and observational study designs to address challenges in livestock systems and inform decision-making, providing producers with evidence to better manage diverse agricultural risks.

A descriptive study approach was employed in Chapter 3 to characterize U.S. veterinarian and feedlot manager decision-making considerations regarding metaphylaxis use in cattle at moderate risk for bovine respiratory disease. A survey design was conducted to assess

how disease risk perceptions, information availability, and management priorities shape intervention (i.e., metaphylaxis) choices. Analysis of survey data revealed areas of both alignment and divergence between the two professional groups, highlighting key factors that influence antimicrobial use in practice and identifying opportunities to improve management practices, enhance communication and information exchange within and across production stages, and promote antimicrobial stewardship.

In Chapter 4, observational auction market data were used in regression analyses to estimate the associations between value-added management program claims and feeder-calf lot sale prices. While observational study-designs provide a lower level of internal validity compared to experimental approaches and generally do not allow causal inference of exposure on outcome, it offers key advantages such as greater external validity (generalizability), the practical ability to assess outcome trends over time, and increased statistical power through use of large, heterogeneous populations derived from real-world contexts. Importantly, this study quantifies realized premiums associated with specific management practices, contributing to a broader, evolving body of economic assessments that are periodically re-evaluated to reflect contemporary production and market conditions, supporting producers in making informed management and marketing decisions under dynamic agricultural markets.

Grounded in this conceptual foundation of agricultural risk, risk perception, attitudes towards risk prevention, and the central role of information, the studies presented in this dissertation apply diverse evidence-generating methods to support evidence-based decision-making, reduce uncertainty, and optimize outcomes in U.S. livestock production systems. Collectively, these studies illustrate how information – derived from different research approaches and information sources – supports strategies to manage production and market risks,

ultimately enhancing the efficiency, profitability, and sustainability of livestock production systems.

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Chapter 2 - Synthesizing evidence and identifying knowledge gaps in the role of swine in Japanese encephalitis virus transmission: a rapid systematic review of the literature

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(Published in *Frontiers in Sustainable Food Systems*, 2024, 8:1455455.
doi:10.3389/fsufs.2024.1455455)

Abstract

The United States is considered a susceptible region with great potential for the introduction of the Japanese encephalitis virus (JEV) given the presence of competent mosquito vector species, susceptible maintenance avian hosts, large populations of susceptible domestic and feral swine, intensive travel and trade activities to and from JEV-endemic countries, similar

climatic and environmental conditions to epidemic countries, and no active JEV surveillance in place. As pigs are considered JEV's primary amplifying host, comprehensively reviewing the available body of evidence, and respective knowledge gaps, pertaining to the role of swine in JEV transmission can provide valuable guidance to decision-makers. Our objectives were to synthesize scientific literature on the role of domestic and feral swine in the transmission of JEV via a rapid systematic review and identify knowledge gaps to determine potential areas amenable for future research. A total of 3,638 records were initially identified. Data were extracted from 227 reports. Transmission of JEV occurs primarily via infected mosquitoes; however, some evidence of direct oronasal transmission between pigs has been reported. Despite pigs exhibiting a short-lived viremia, JEV has been demonstrated to persist longer in their tonsils. In sows, JEV infection may cause reproductive disorders, and although maternal antibodies can confer protection for several months under field conditions, naïve piglets can exhibit neurologic signs which may progress to wasting disease. Studies evaluating breed or sex reported no association with JEV seropositivity. Application of biosecurity practices and vector control are recommended as preventive measures against introduction and spread of JEV in swine farms. Although there is no JEV vaccine licensed for pigs in the United States, live attenuated vaccines were reported to elicit superior immunogenicity compared to inactivated vaccines used in endemic countries. Summarizing the current understanding of JEV infection in swine can guide researchers, stakeholders, and policymakers in prioritizing research efforts and developing effective countermeasures. This is particularly crucial in the event of an outbreak in the United States, where preemptive measures can help minimize the spread of the virus, safeguard both human and animal populations, and ensure the long-term sustainability of the swine production sector.

Key words: Japanese encephalitis virus, Rapid systematic review, Swine, Transmission, Knowledge synthesis

Introduction

Japanese Encephalitis (JE) is an emerging, zoonotic disease transmitted by mosquitoes, primarily *Culex* but also from other genera including *Aedes*, carrying JEV (family *Flaviviridae*: genus *Flavivirus*). The virus is maintained and circulates among mosquito vectors and vertebrate hosts (Le Flohic et al., 2013). Ardeid wading birds, such as egrets and herons, and both domestic and feral swine are regarded as the primary natural reservoirs and amplifying hosts of JEV, respectively. Swine are considered amplifying hosts, as they can produce and maintain high levels of viremia, allowing for continued vector-borne transmission (Ricklin et al., 2016b; Ladreyt et al., 2019; Williams et al., 2019). Although the role of swine as key contributors to JEV amplification was questioned when their removal from specific endemic regions did not affect the broader transmission dynamics (van den Hurk et al., 2008), their involvement in the JEV cycle remains crucial due to its significant socioeconomic impact on humans. Clinical signs reported from JEV infection include reproductive issues in sows and boars, and fever, depression, and neurologic signs in piglets (Park et al., 2022). Other vertebrates (i.e., humans, horses, and cattle) are considered dead-end hosts, most displaying no signs of infection (except humans and horses), and producing levels of viremia that are insufficient to infect new mosquito vectors (Figure 2.1).

In humans, JEV infection can cause inflammation of the brain (encephalitis), which can lead to fever, headache, respiratory distress, gastrointestinal pain, confusion, seizures, and, in

some cases, death (Kumar et al., 1990; Campbell et al., 2011; Kliegman et al., 2015). Less than 1% of human cases are accompanied by symptoms, however 30% of symptomatic cases are fatal (Campbell et al., 2011). The global incidence of JE is uncertain due to variations in the effectiveness and quality of JE surveillance in endemic countries (Jayatilleke, 2020), and the availability of diagnostic testing worldwide. Researchers have estimated the yearly occurrence of human JE cases to range from 50,000 to 100,000 in countries where JEV is present (World Health Organization, 2006; Campbell et al., 2011; Quan et al., 2020). Although there are vaccines available to prevent JE, there is no specific antiviral treatment, and treatment consists of supportive care to relieve symptomology.

International trade and globalization, presence of competent vectors, susceptible amplifying and maintenance hosts, and optimal environmental conditions make the United States (U.S.) susceptible to the introduction and establishment of JEV (Oliveira et al., 2018a). As the world's third-largest producer and consumer of pork and pork products [United States Department of Agriculture—Economic Research Service (ERS), 2024], the incursion of JEV into the United States could substantially impact the national economy. Concurrently, in the past decade, federal agencies have shown increased interest in funding research to enhance our understanding of the impact of invasive feral swine in the United States, whose population is estimated at over 6 million (United States Department of Agriculture, n.d.). This surge is driven by gaps in our knowledge about how this species affects swine disease transmission dynamics in the United States (Brown et al., 2024). Since pigs are considered an amplifying host of JEV, a systematic review of the literature and identification of knowledge gaps can inform researchers, stakeholders, and policymakers on effort prioritization, development of interventions to prevent JEV introduction, and evaluation of disease control measures in the event of a JEV incursion.

While recent reviews have summarized existing knowledge regarding JEV transmission routes, patterns of viremia, and epidemiological cycles and systems (Ladreyt et al., 2019; Park et al., 2022), some knowledge gaps regarding the role of swine in JEV transmission remain. A robust understanding of the role of swine as an amplifying host for this virus is crucial for animal and public health authorities when devising interventions to curb JEV spread. The objectives of the present study were to synthesize scientific literature on the role of domestic and feral swine in the transmission of JEV, via a rapid systematic review, and identify gaps in the existing knowledge to determine potential areas amenable for future research.

Methods

A rapid review of the literature was conducted according to an a priori developed protocol (Veloso et al., 2023) incorporating streamlined systematic review methods proposed by Garritty et al. (2021). Post hoc changes to the protocol were incorporated as described in the protocol's amendments section, and the updated version was made available in the same repository (K-Rex/CORE collection). This review was not registered a priori. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) were followed for reporting. We chose to utilize the systematic review label as our aim was to, not only map themes, but also synthesize data addressing specific questions which are essential to decision-makers. However, we recognize that this review's methodology encompasses not only the principles of systematic reviews but also those of scoping reviews.

This rapid systematic review on the role of swine, both domestic and feral, in the transmission of JEV, was guided by the following research questions:

1. What are the routes of infection/transmission in swine?
2. Do swine exposed to different JEV genotypes present different

macroscopic and microscopic pathological lesions?

3. Do swine exposed to different JEV genotypes exhibit variation

in viral organotropism?

4. Do swine exposed to different JEV genotypes exhibit variations in clinical signs?

5. What diagnostic tests have been used to detect JEV in swine?

6. What is the sensitivity and specificity of diagnostic tests that have been evaluated for the detection of JEV in swine?

7. What is the JEV seroprevalence in swine?

8. Do swine demographics serve as risk factors for the proportion of JEV infection in swine?

9. Do the size, type, location, or other environmental characteristics of swine operations serve as risk factors for the proportion of JEV infection in swine?

10. What surveillance efforts have been conducted at the animal or farm level to detect JEV in swine?

11. Which JEV vaccines have been evaluated for their efficacy in swine?

12. What is the basic reproduction ratio (R_0) for JEV in swine populations?

13. What biosecurity measures have been evaluated regarding the transmission of JEV in swine?

14. Can JEV be transmitted through/detected in pork products?

Expert and stakeholder engagement

Due to the broad scope of our objectives, expert opinion from swine producers, veterinarians, researchers, and other stakeholders from the United States and Australia with content expertise in the areas of commercial swine production and JEV was sought to prioritize

research questions and identify critical outcomes. Expert opinions were gathered through emails and an electronic survey. Results from the electronic survey were strictly used to inform the review process and are not reported as a finding of this review.

Information sources

Searches of information sources were performed between August and October 2022. The bibliographic databases used were Scopus and Web of Science, which includes the following databases: Web of Science Core Collections, KCI-Korean Journal Database, MEDLINE, and SciELO Citation Index. Due to the limited peer-reviewed literature available on feral swine, we performed additional hand-searches to capture records on feral swine that may not have been indexed in the bibliographic databases. The other sources searched were United States government websites [United States Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS), Centers for Disease Control and Prevention (CDC), and USDA National Institute of Food and Agriculture (NIFA) Current Research Information System (CRIS)] and a repository (USDA Wildlife Services Digital Collection) as well as two citation searches. The first citation search was an author citation search of Dr. Vienna Brown's google scholar profile, given her contributions to the field of feral swine management, and the second was a search of the reference list of the WHA fact sheet on Japanese encephalitis (Wildlife Health Australia, 2022), which reported information about JEV in wildlife in response to the latest JEV outbreak in Australia. All sources queried, dates searched, search terms, and the number of records are reported in Supplementary Table S1.

Eligibility criteria

Using a Population, Outcome, and Study design (POS) framework, two sets of eligibility criteria were designed, one for the reports from the bibliographic databases and one for reports

gathered from the other sources, as the population of interest was different for the reports from the bibliographic databases (i.e., domestic and feral swine) and reports gathered from other sources (i.e., feral swine only). All criteria are summarized in Table 2.1.

Search strategy

Our search strategies were informed by the POS framework described above and in Table 2.1. The full search strategies for the bibliographic databases are presented in Supplementary Table S1, but in brief, we searched for “Japanese encephalitis virus” and “swine” and restricted to reports written in English. Given the broad themes/ questions covered and the limited search capabilities of some of the websites searched, we trialed multiple combinations of “Japanese encephalitis virus” and its synonyms (i.e., “Japanese encephalitis,” “Japanese B encephalitis,” “JEV,” “JE,” “summer encephalitis,” “viral encephalitis,” “viral meningitis,” “Russian autumnal encephalitis,” “viral encephalitis”) along with “feral swine” and synonyms for feral (i.e., “wild,” “game,” “free range,” “ranging,” “free-roaming,” “undomesticated,” “non-domesticated”) and swine (i.e., “pig,” “hog,” “boar,” “pork,” “*Sus scrofa*”). Based on these preliminary searches, we identified the combinations of search terms that yielded the most relevant records, unique to each website. For the hand-searching of citations, titles from reference lists were searched for language referring to “Japanese encephalitis virus” and “feral swine” or relevant synonyms.

Selection process

Records from the bibliographic databases were downloaded as Research Information Systems (RIS) files and then uploaded into Covidence (Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia). Covidence’s deduplication tool was used to remove duplicate records before screening. Relevance screening of records was performed by two reviewers (VH, CH). One reviewer (VH) screened all records utilizing the following

questions as a screening tool: (1) Are the title and abstract written in English? (2) Does the study population consist of swine (*Sus scrofa* or *Sus domesticus*)? (3) Does the abstract describe aspects of JEV? (4) Does the abstract describe a peer-reviewed article? (5) Does the abstract describe original research, a Systematic Review, or a Meta-analysis? (6) Does the study involve a transmission aspect of JEV in swine species, diagnostic test performance for JEV, or JEV vaccine efficacy? and (7) Is this abstract/article relevant? To each question, potential answers included “yes,” “no,” or “unclear.” A “no” answer for any question resulted in the exclusion of the record. If a record received an “unclear” answer for any question, the full report was retrieved and was screened with the previously described screening tool by another reviewer (CH). If a consensus about a record’s relevance could not be achieved, at any point in the screening process, then a tertiary reviewer (NC) was consulted.

To screen the records from the government websites and repository, a primary reviewer evaluated records for eligibility (ME) based on title only. The record title had to include a reference to JEV and feral swine, or their synonyms. If a record received an “unclear” or “yes” answer, the full report was retrieved and screened by two reviewers (ME, VH) using the previously described screening tool, except the population in question 2 was restricted to *Sus scrofa*. Disagreements between the primary and secondary reviewer were resolved via consensus, or through a tertiary reviewer (NC, CH) when a consensus could not be achieved.

Data collection process

A data collection tool was designed using Microsoft Excel (Microsoft Office Professional Plus 2019). Data were collected from eligible reports in duplicate by pairs of reviewers working independently (VH, CH, SE, NC, AT, and TM). Discrepancies were resolved by consensus or by a tertiary reviewer (VH, CH, and NC).

Data items

All key variables identified for data collection and any data simplifications are described in Supplementary Table S2. Citation information was extracted at the report level, while the remaining data items were extracted at the study level, considering that one report could contain descriptions of multiple studies. For each study, characteristics of the study population (breed, sex, and age), study characteristics (study type and location, sample size, design structure, and JEV case definition), and the study outcome measures that were relevant to our research questions were extracted. The extraction of the data items was tailored to the study design structure. For observational studies, risk factors were extracted. For experimental studies, interventions (e.g., vaccination, preventive/biosecurity measures, and surveillance strategy) and the route of exposure to JEV [i.e., challenge (along with dose, strain, and route) or natural] were extracted. Relevant outcomes including transmission routes, pathological lesions and viral organotropism, clinical signs, seroprevalence, and the basic reproduction ratio were extracted at the reported outcome level (i.e., animal or herd level). For studies evaluating diagnostic test performance, the outcomes of relevance included sample type, diagnostic sensitivity, diagnostic specificity, analytical sensitivity, analytical specificity and cross-reactivity.

Data synthesis methods

Data were summarized by outcomes for each research question by filtering on key data items using the R language or Microsoft Excel, and presented in either a tabular format or as text depending on the number of relevant reports. Below we describe the criteria used to synthesize data by theme/research question. If a research question was addressed by a systematic review identified through our search strategy, and no further substantial information was found, we refer

the reader to the previous review. This was the case for the research questions regarding seroprevalence and routes of transmission for JEV in swine populations.

Pathological lesions and viral organotropism

Reports containing studies that described gross pathology, histopathology, and/or viral organotropism results were synthesized and organized by JEV genotype, system affected, type of exposure, inoculation route, and dose. Included in the synthesis table were reports that described vaccine efficacy studies; however, only animals that were challenged with JEV, but not given a vaccine (i.e., a positive control), were included in the synthesis table.

Clinical signs

Reports containing studies that reported clinical signs in unvaccinated swine infected with JEV were summarized. Synthesized data were organized by clinical sign category, by age category (i.e., nursing, weaning, finishing, or mature), then by JEV genotype, and within genotype, alphabetically by strain, and then inoculation route.

Summarized data include report counts, population description, infection strain (genotype), infection route and dose, number and percentage of animals affected out of the total observed, and respective references.

Diagnostic tests

Two questions were evaluated regarding diagnostic tests for JEV. To evaluate the research question of “What diagnostic tests have been used to detect JEV in swine?,” any reported diagnostic test used to detect JEV in swine was summarized and organized by the diagnostic test method category. The categories used were adapted from the list of approved tests for detection of JEV as outlined in the World Organisation of Animal Health’s (WOAH) Manual of Diagnostic Tests and Vaccines for Terrestrial Animals (World Organisation for Animal

Health, 2023). The table details the test name, test description, sample type used for the diagnostic test, and respective references.

To evaluate the research question “What is the sensitivity and specificity of diagnostic tests that have been evaluated for the detection of JEV in swine?,” we synthesized results from reports where the diagnostic sensitivity and specificity of novel (i.e., new) diagnostic tests for detecting JEV in swine were evaluated. For inclusion in the synthesis table, researchers needed to compare the novel test to a reference test. Reports were organized by the WOAHP test method categories, and within each category reports were organized alphabetically by test name. Summarized information included the test method and name, sample type used, microbial species evaluated for test cross-reactivity, cross-reactivity of the test to *Flavivirus* spp., analytical sensitivity of the novel test, name of the reference test, diagnostic sensitivity and specificity of the novel test, and the respective references. A separate table was created for results from reports that met the inclusion criteria, but only reported analytical sensitivity and failed to report diagnostic sensitivity and specificity.

Risk factors

Reports including studies reporting a statistical test evaluating the association between animal-level (i.e., sex, breed, and/or age) or farm-level (e.g., environmental, management) characteristics with JEV seroprevalence, seroconversion, or viremia were synthesized. Studies evaluating swine demographic risk factors of breed, sex, and age were synthesized and organized in chronological order of publication, within each swine purpose category (domestic swine presented first followed by feral swine) by risk factor. Risk factors for domestic swine operations were grouped by farm location/geography, farm management, resources, and infrastructure, or host and vector presence around the farm. Studies are presented in chronological order of

publication within each risk factor group. Summarized data include the total number of reports that evaluated each risk factor, risk factor level of stratification, swine population description, sample size, seroprevalence and/or odds ratio for JEV positivity, statistical significance of differences, and respective reference.

Surveillance and biosecurity

Reports including studies that statistically evaluated the effect of a surveillance strategy or biosecurity intervention on any component of JEV transmission in swine were synthesized. Results are discussed in the text.

Vaccine efficacy

Reports that assessed vaccine efficacy by comparing JEV vaccinated and challenged swine to positive controls, in experimental studies, were synthesized. Reports within the synthesis table are organized by type of vaccine evaluated (live-attenuated, killed, or other), then within each type in chronologically ascending order, and alphabetically by author within year. Summarized data include vaccine information, including strain and producer, study design and challenge strain, population and sample size of vaccinated swine, evidence used to determine efficacy, and respective references.

Basic reproduction ratio

Reports where authors modeled JEV transmission and estimated the basic reproduction ratio were synthesized. Information regarding model compartments, the control strategy evaluated (when applicable), the outcomes measured to evaluate the corresponding control strategy, the location, and the respective report references was included in the synthesis table. Reports are organized based on the similarity of the compartments evaluated across populations.

Pork products

Reports describing JEV detection in sample types of processed pork or pork products were sought for synthesis; however, no reports were obtained through our search strategy. Therefore, our findings regarding the existing knowledge gap pertaining to the safety and potential transmission of JEV via pork products are reported in the text.

Identification and characterization of knowledge gaps

Identification and characterization of knowledge gaps was performed using the framework proposed by Robinson et al. (2013), which was developed to identify and classify research gaps in systematic reviews. After adapting the knowledge gaps worksheet from Robinson et al. (2013) into a Microsoft excel worksheet (Supplementary material 2), reviewers (NC, AD, CH, and VH) identified knowledge gaps in the evidence synthesized for each research question and characterized the reasons for the gaps individually, each addressing a different research question. A knowledge gap synthesis was not performed when few or no reports were identified regarding the research question (i.e., surveillance, biosecurity, and pork products), or when the research question was not amenable for the knowledge gap tool utilization (i.e., diagnostic tests used, diagnostic tests evaluated, and vaccine efficacy). The following categories were utilized to classify the reason for the gap: insufficient or imprecise information, inconsistent or unknown consistency, and not the right information. Details of the explanation for each category can be found in Robinson et al. (2013) and in the Key section of the knowledge gap tool.

Results

Study selection

A total of 3,638 records were identified, including 3,163 from bibliographic databases and 475 from other sources. Two-hundred and twenty-six reports identified from the

bibliographic database search and one report from other sources were included in the review for a total of 227 reports, describing 353 studies. A flow chart detailing the results of the screening process is presented in Figure 2.2.

Study characteristics

All reports which were included in this rapid review are organized by study design in Supplementary Table S3 and, with detailed citation references listed in Supplementary material 3. Ninety-nine reports described 162 experimental studies, 135 described 180 observational studies, 10 detailed JEV modeling studies, and five reports were systematic reviews. The reports included in this review were published between 1947 and 2022 (median 2009). Nearly 40% of the reports originated from JEV endemic countries (Bangladesh, Cambodia, China, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Sri Lanka, Thailand, and Vietnam), 37% were from JEV epidemic countries (Australia, Japan, North and South Korea, Nepal, and Taiwan), 16% were from India (where the northern region experiences JEV peak seasons, while the southern region observes year-round transmission), and the remaining reports were from JEV-free countries. All systematic reviews were published within the past 10 years (between 2015 and 2022). The oldest reports included in this review (i.e., 1947–1970) primarily focused on describing infection routes, pathological lesions, organotropism, and clinical signs. Reports evaluating risk factors associated with the proportion of JEV infection in swine populations were more recent, with the majority published between 2009 and 2021.

Syntheses of results

The information gathered on each research question of interest is described below and in synthesis tables, which are detailed in Table 2.2 along with the number of reports synthesized.

Knowledge gaps associated with each research question are detailed in their respective sections, summarized in Table 2.2, and the completed tools are in Supplementary material 2.

Transmission routes

The mechanisms of JEV transmission in pigs have been comprehensively summarized in the systematic review by Ladreyt et al. (2019), and our review of the literature did not uncover any additional research warranting an updated synthesis on transmission routes in swine. None of the reports included in this review described studies investigating JEV excretion and transmission through abortion fluid, a knowledge gap highlighted by Ladreyt et al. (2019). Lastly, the transmission of JEV through artificial insemination, via semen, or by the transfer of embryos derived from JEV positive animals, remains to be evaluated since the detection of JEV in swine semen and embryos by Ogasa et al. (1977) and Yoshida et al. (1981).

Pathological lesions and viral organotropism

Twenty-four reports describing macroscopic, microscopic pathological findings, and/or viral organotropism, associated with JEV genotype (GI, GIII, or unknown) and inoculation route and dose, were identified and are summarized in Supplementary Table S4. Pathological lesions and/or organotropism associated with JEV GI infection in swine was described in five reports, GIII infection was described in 14 reports, and nine reports described pathological and/or viral organotropic results from a JEV infection with a strain of unknown genotype.

Central nervous system

Hemorrhages in the brain and spinal cord of nursing pigs naturally exposed to either JEV GI or JEV of an unknown genotype were described by Cao et al. (2011) and Burns (1950), respectively. Yamada et al. (2004, 2009) reported brain edema in weaning aged pigs on days 3- or 7-day post inoculation, but this result was not consistent across studies or among JEV

challenge strains (unknown genotype). Meiklejohn et al. (1947) also reported the inconsistent observance of hyperemia and necrosis in the brain of finishing aged pigs challenged with JEV (unknown genotype). No reports described macroscopic pathological lesions of the CNS system associated with JEV GIII infection.

After challenges with JEV GI intravenously (Park et al., 2018) and subcutaneously (Fan et al., 2018), CNS organs including nervous tissue, cerebellum, thalamus, and frontal and temporal lobe tested positive for JEV RNA 3-day post inoculation, and brain tested positive for JEV RNA 8-day post inoculation, respectively. Park et al. (2018) also isolated infectious virus from CNS tissues. However, at 11-day post inoculation, after both an intradermal and intravenous challenge, Ricklin et al. (2016a) reported that no viral RNA was detected in brain tissue. A similar pattern was found in the results of challenges with JEV GIII; JEV RNA detection and virus isolation in CNS organs varied depending on the organ, inoculation route, and dose. Sazawa et al. (1969a) reported viral isolation from both the brain and spinal cord after inoculation intracerebrally, just in the brain after intranasal inoculation, and in neither the brain nor spinal cord after a subcutaneous inoculation. Ricklin et al. (2016a) detected JEV RNA in the thalamus and basal nuclei after an oronasal inoculation, a result corroborated by the findings of García-Nicolás et al. (2017), however Ricklin et al. (2016a, 2016b) detected little to no viral RNA in the meninges, choroid plexus, and spinal cord after a joint intradermal, intravenous inoculation.

Lymphatic system

Only Burns (1950) described macroscopic pathological lesions in the lymphatic system, specifically lymphadenomegaly of the thoracic and mesenteric lymph nodes as well as splenic necrosis, following a natural JEV infection (unknown genotype) in nursing aged pigs. No reports

described macroscopic pathological lesions of the lymphatic system associated with any specified JEV genotype infection.

All reports (Ricklin et al., 2016a; Fan et al., 2018; Park et al., 2018) describing viral organotropic results in organs of the lymphatic system after challenges (intradermal, intravenous, and subcutaneous) with JEV GI reported JEV RNA detection in bone marrow, lymph nodes, spleen, thymus, and/or tonsils 3–11-day post inoculation and at 25-day post inoculation in tonsils. Ricklin et al. (2016a) and Park et al. (2018) also isolated JEV from tonsils after intravenous inoculations at 10^6 and 10^7 TCID₅₀, respectively. Similarly, all reports describing challenges with JEV GIII via intradermal, intranasal, both intradermal and intravenous, oronasal, and/or subcutaneous inoculation (Ricklin et al., 2016a, 2016b; García-Nicolás et al., 2017; Fan et al., 2018; Redant et al., 2020) reported the detection of JEV RNA in lymphatic organs, specifically bone marrow, lymph nodes, spleen, thymus, and/or tonsils 5–11-day post inoculation and at 21-day post inoculation in tonsils. Ricklin et al. (2016b) also reported isolating live virus in the tonsils up to 11-day post inoculation using a combination intradermal and intravenous inoculation method totaling 10^7 TCID₅₀. Live JEV was isolated from lymph nodes, consistently, 2, 3, and 4 days after intracerebral, intranasal, and subcutaneous inoculation, and in spleens 2, 3, and 4 days after intracerebral inoculation, and up to 6 days after intranasal and subcutaneous inoculation (Sazawa et al., 1969a). However, Redant et al. (2020) reported no infectious virus in prescapular lymph nodes and spleen following intranasal inoculation at 10^5 TCID₅₀.

Reproductive system

Shimizu et al. (1954) and Desingu et al. (2016) both described JEV GIII infection of pregnant sows resulting in the delivery of mummified fetuses or stillborn piglets with encephalitis and lymph node congestion in a portion of the affected litters. Piglets that were born

alive from the infected sows were described as either normal or presenting with hydrocephalus and subcutaneous edema. Yoshida et al. (1981) described the recovery of affected embryos from JEV GIII infected sows. Similar macroscopic pathological findings were reported in sows infected with JEV strains of an unknown genotype along with reports of placental hemorrhage and necrosis (Fujisaki et al., 1975; Takashima et al., 1988). No reports described macroscopic pathological lesions of the reproductive system associated with JEV GI infection.

Only one report described organotropic results of GI infection in the reproductive system (Nie et al., 2022); they reported that testicular fluid and placenta and umbilical cords of aborted fetuses from naturally exposed, symptomatic boars and sows, respectively, tested positive for JEV RNA. Six reports described organotropic results of GIII infection in the reproductive system; three described studies with a natural exposure (Fan et al., 2010a; Teng et al., 2013; Desingu et al., 2016) and three described studies with a challenge of an unknown route (i.e., not reported clearly by authors) (Shimizu et al., 1954; Yoshida et al., 1981; Zheng et al., 2019). These reports describe similar results to those where viral GI RNA was detected. In addition, four reports reported isolation of JEV from fetuses and placentas from a challenged sow (Shimizu et al., 1954; Yoshida et al., 1981), fetal cerebral fluid from fetuses of naturally exposed sows (Fan et al., 2010a; Teng et al., 2013), and seminal fluid from naturally exposed boars (Teng et al., 2013). In addition, Zheng et al. (2019), reported that spermatogenic and Sertoli cells were positive for JEV E-antigen after a challenge.

Multiple systems

Pleural effusion was reported in five of 12 weaning aged pigs 5- and 7-day post inoculation with JEV GIII (Ricklin et al., 2016b), as well as in nursing aged pigs (Burns, 1950).

Burns (1950) also reported subcutaneous edema, hepatic necrosis, and petechial hemorrhages of serosal membranes in nursing aged pigs.

Ricklin et al. (2016a) were the only authors to report on JEV GI RNA detection in other systems; detecting viral RNA in the ileum, kidney, liver, and skeletal muscle 3–11-day post inoculation either intradermally or intravenously at 10^6 TCID₅₀. After inoculation (intracerebral, intranasal, and subcutaneous) with JEV GIII, infectious virus was isolated from lungs, livers, and/or kidneys (Sazawa et al., 1969a). However, Redant et al. (2020) reported that no JEV RNA was detected in liver and kidneys at 10- and 14-day post inoculation intranasally or intradermally with 10^5 TCID₅₀. Whereas Ricklin et al. (2016b) reported JEV RNA detection in the distal ileum, liver, and kidneys up to 11-day post inoculation, low to negative JEV RNA detection in skeletal muscles at 3, 5, and 7 days post inoculation, and low RNA detection in peripheral blood at 3 days post inoculation with a combined intradermal and intravenous method at 10^7 TCID₅₀. Ricklin et al. (2016a) also reported detecting JEV RNA in the ileum after oronasal inoculation. In addition to corroborating this data, García-Nicolás et al. (2017) detected JEV RNA in the jejunum and detected low levels of RNA in urine from one animal.

Knowledge gaps

Our research question was to compare the pathological and organotropic effects between JEV genotypes in swine. The only identified genotypes used in laboratory challenge and natural exposure studies with domestic swine were genotypes I and III, although there were several challenge strains used with unknown genotypes. This creates a knowledge gap of the pathological and organotropic effects of infection with genotypes II, IV, and V in domestic swine of any age and breed. Additionally, we did not identify any reports describing pathological lesions or organotropism associated with any JEV infection in feral swine.

Only five reports identified the JEV genotype associated with the macroscopic pathological lesions described within the reports. No reports contained a direct comparison of macroscopic pathological lesions between genotypes I and III, nor did any reports describe lesions associated with JEV GI infection in any system apart from the CNS system. The limited number of reports creates a knowledge gap for comparing macroscopic pathological lesions among JEV genotypes.

There were a number of reports that examined organotropism in swine after JEV infection with genotypes I and III, however patterns from comparing the two could not be made descriptively as there likely are a number of confounding elements, such as inoculation route, dose, incubation period, and organ system investigated, that need to be considered. A further meta-analysis of this outcome is needed to close this knowledge gap.

Clinical signs

A total of 27 reports describing clinical signs associated with JEV infection in domestic swine were identified and are summarized in Table 2.3. The description of clinical signs was highly variable across swine age categories and among reported JEV genotypes (GI, GIII, and unknown). Fever observed at 2–11-days post infection was the most frequently reported clinical sign across age categories but was not reliably observed in all animals within a study population. Similarly, reproductive failure (including aborted litters and stillborn fetuses) in mature females was commonly reported, but also was not always observed in a large proportion of the study populations. Anorexia observed at 3–6-day post infection, neurological signs observed 3–27-day post infection, and depression lasting up to 13-day post infection were all reported in at least a portion of the study populations of nursing, weaning, and finishing-aged pigs with no discernible association with any JEV genotype. The occurrence of conjunctivitis (Meiklejohn et al., 1947),

decreased fecal output (Ricklin et al., 2016a, 2016b), and weight loss (Park et al., 2018) were each only reported by a single research group within a single age category. In contrast to the other reports, four reports described a complete absence of clinical signs in all the pigs within their study populations (Shimizu et al., 1954; Yang et al., 2004a; Cappelle et al., 2016; Xie et al., 2022).

Only two reports directly compared differences in clinical signs in domestic swine infected with JEV GI versus GIII (Fan et al., 2018, 2019). In those reports, fever in weaning-aged pigs was consistently reported following JEV GI infection, whereas the presence of fever in weaning-aged pigs following JEV GIII infection was dependent on the challenge dose. However, sample sizes were small in these studies with three or four animals per treatment group.

No reports (0/27) describing clinical signs in feral swine were identified during this review. Small sample sizes, reporting deficiencies, and inconsistency in observed clinical signs were the most frequent limitations for drawing conclusions for specific age categories of swine. There were no studies detailing clinical signs associated with JEV genotypes II, IV, or V in any swine population.

Diagnostic tests

A total of 211 reports described the use of a diagnostic test ($n = 51$) to detect evidence of JEV exposure in biological samples from swine (Supplementary Table S5). According to WOA (World Organisation for Animal Health, 2023), the hemagglutination inhibition test (HI) is the only recommended test for determining an animal's freedom from infection, determining immune status post-vaccination, and surveilling for JEV. For confirmation of clinical cases, WOA also recommends virus isolation, real time reverse-transcription PCR (RT-PCR), or a virus neutralization (VN)/plaque reduction neutralization test (PRNT), in addition to HI. Real

time RT-PCR, enzyme-linked immunosorbent assay (ELISA), and VN and PRNT are recommended, with limitations, for surveillance and determination of an animal's freedom from infection. Among reports included in this review, 97 utilized HI, with publication dates ranging from 1958 to 2021. This is the third longest method in use, surpassed only by virus isolation (1957–2022) and virus neutralization tests (1947–2022). ELISA tests have been reported in published literature since 1982 and RT-PCR since 2001. For virus detection, using a combination of testing methods is recommended. Among reports included in this review, 71 used multiple testing methods to detect JEV.

Thirty-seven reports evaluated the performance of 43 novel diagnostic tests against a reference test. Diagnostic test sensitivity and/ or specificity were reported for the novel tests in 28 of these reports. The diagnostic test type, sample type tested, microbial species tested for cross-reactivity, cross-reactivity results to other flaviviruses, analytical sensitivity, the reference test name, and diagnostic sensitivity and specificity for the novel test are reported in Supplementary Table S6a, and a condensed table of these results is reported in Table 2.4. Nine reports only included results for analytical sensitivity and cross-reactivity of the novel test, and not diagnostic sensitivity and specificity. These results are summarized in Supplementary Table S6b.

Thirteen novel tests were designed for virus detection, 85% ($n = 11$) of which utilized molecular methods. Twenty-one tests were designed to detect antibodies, 71% ($n = 15$) were ELISAs. Five reports published in the early 1980's first described the evaluation of ELISAs and reported diagnostic sensitivity values ranging from 82.9 to 100% and diagnostic specificity values ranging from 16.9 to 100%. The remaining reports evaluating ELISAs were published after 2005 and report diagnostic sensitivity values of 62.8–100% and diagnostic specificity

values of 78.9–98.6%. Reports that evaluated molecular tests have all been published since 2012 and report variable diagnostic sensitivity values.

Eight of the novel tests were assessed for cross-reactivity to other flaviviruses, specifically Dengue, West Nile, Yellow Fever, and Zika viruses (Dhanze et al., 2015; Kolhe et al., 2015; Wu et al., 2017; Pantawane et al., 2019; Wang et al., 2020), only one of which reported cross-reactivity to West Nile virus (Kolhe et al., 2015). Twenty-six of the 43 evaluated tests reported the results of cross-reactivity assessment to other viruses and bacteria (Supplementary Tables S6a,b).

Two reports (Konishi and Yamaoka, 1982, 1983) used multiple different swine sample types to compare standard ELISA and HI methods with a rapid ELISA; however, because the authors only reported the correlation coefficients for these comparisons, these reports were not included in the summary tables.

Seroprevalence

The seroprevalence of JEV in swine populations, both domestic and feral, has been extensively examined, documented, and summarized elsewhere. This review identified five systematic reviews which have summarized JEV seroprevalence in swine populations, both domestic and feral, across different endemic regions and years (Lopez et al., 2015; Oliveira et al., 2017; Oliveira et al., 2018b; Ladreyt et al., 2019; Suresh et al., 2022).

Two of the 12 reports identified in this review, which described studies conducted in feral swine populations, were not included in prior reviews. These reports described observational studies, conducted in 2019, in JEV-endemic countries (China, Japan), with the primary outcome being evidence of JEV exposure in feral swine, as demonstrated by detecting JEV antibodies (Guo et al., 2019; Yonemitsu et al., 2019). While most studies on feral swine populations

described the level of JEV antibody seroprevalence in serum samples, Yonemitsu et al. (2019) utilized heart and diaphragm meat juice as the diagnostic sample. After comparing results obtained from serum samples, the authors concluded that meat juice is a suitable specimen for detection of anti-JEV antibodies using ELISA (Yonemitsu et al., 2019). When evaluating knowledge gaps for this, and other, research questions of interest, it became evident that research on JEV in feral swine populations was largely unavailable.

Risk factors

Swine demographic risk factors

Summaries and specifics of the studies that evaluated the association between animal breed, sex, and/or age with JEV seroprevalence in swine are reported in Table 2.5. No significant association between domestic swine breeds and JEV seroprevalence was reported in any of the six studies in which it was evaluated. In five of the six studies, local or indigenous breeds were compared to unspecified commercial and cross breeds, whereas one study compared Vietnamese Duroc, Landrace, Yorkshire, and hybrid breeds. No significant association between sex and JEV seroprevalence was reported in any of the five studies where it was evaluated, two of which were conducted in feral swine populations (Table 2.5).

Seven of 11 studies reported a risk of increased JEV seroprevalence with increasing age in domestic swine. Three studies compared groups of animals younger than 12 months, three compared animals younger than 12 months to animals 12 months and older, and one study evaluated age as a continuous variable (3 to >12 months; Henriksson et al., 2021). Alternatively, one study (Kumar et al., 2018) reported increased age as a protective factor for JEV seropositivity in domestic swine, comparing “young” and “adult” animals, defined by the authors as younger than 6 months and 6 months and older, respectively. One study (Ohno et al., 2009)

evaluated the association of age and JEV seroprevalence in feral swine and reported no significant association. The age groups compared, “juvenile” and “adult,” were determined by animal weight, less than 50 kg and over 50 kg, respectively.

From our data synthesis, the associations between breed or age and JEV seroprevalence in swine are not knowledge gaps, although there are some specific caveats which limit external validity. Breed is not statistically associated with JEV seroprevalence in domestic swine when comparing local indigenous breeds versus imported breeds in JEV endemic areas. With limited studies ($n = 5$), the association between sex and JEV seroprevalence in feral and domestic swine remains inconclusive and therefore, a knowledge gap. Given the number of studies ($n = 11$) and consistency between them, we concluded that increased age is a risk factor for increased JEV seroprevalence in domestic swine in JEV endemic areas, however there are too few studies ($n = 1$) in feral swine to make any conclusions and this remains a knowledge gap. Reports on demographic risk factors in both domestic and feral swine focused solely on JEV seroprevalence. However, evaluating demographic risk factors using outcome measures that include a time component, such as incidence rate, remains necessary for a complete understanding of swine population susceptibility to JEV infection.

Swine operation risk factors

Only four reports included studies that statistically evaluated the association between farm-level risk factors and JEV seroprevalence in swine. The specific risk factors evaluated were: elevation, locality, proximity to a rice paddy, proximity to stagnant water (farm location), vehicular access, farm water source, animal source, toilet-related amenity, electricity in the home, piped water at home, waste management, feed type, swine housing type, size of operation, floor type, mosquito control (farm management, resources, and infrastructure), presence of

mosquitoes, presence of ardeid birds, and presence of other animals (host and vector presence around the farm). Summaries of the associations between these risk factors and JEV seroprevalence in swine are reported in Table 2.6.

Two reports (Thakur et al., 2012; Kumar et al., 2018) were responsible for most of the risk factor evaluations of farm location, farm management, resources, and infrastructure, and host and vector presence around the farm. The other two reports included studies evaluating housing types as a risk factor. Three of the four studies did not find a statistical association between swine housing type and JEV seroprevalence in swine (Table 2.6). Conlan et al. (2012) evaluated the association between housing type and JEV seroprevalence in the dry and wet seasons, reporting that during the dry season, free-range swine had lower JEV seroprevalence than penned swine. In addition to the associations reported in Table 2.6, Thakur et al. (2012) reported results on vehicular access, electricity in the home, piped water at home, waste management, swine feed type, size of operation, pen-floor type, mosquito control, and presence of other animals around the farm, but none were significantly associated with swine JEV seroprevalence in univariable models.

For all factors evaluated, the limited number of studies precludes general conclusions from being made. The sole risk factor with more than two studies, housing type, is relatively consistent, in that no significant association was found between housing type and JEV seroprevalence; however, the interaction of seasonality from the Conlan et al. (2012) studies and discrepancy between the types of housing utilized in Ladreyt et al. (2020) also limits the general conclusions that can be drawn from the broad category of housing type.

Surveillance

This review did not identify any reports evaluating the effectiveness of surveillance strategies (e.g., serological surveillance or systematic surveys of herds) for JEV detection in swine populations. Our search strategies and screening process would have precluded reports evaluating strategies that surveilled other species (i.e., mosquitoes) or other species used as sentinels to detect JEV presence/ levels in swine populations. Although the lack of reports on the effectiveness of specific surveillance strategies in swine populations indicates a knowledge gap in this area for both domestic and feral swine in JEV endemic and non-endemic areas, a more specific search on surveillance strategies is needed to understand the scope of the gap.

Vaccine efficacy

Supplementary Table S7 describes the results of 19 reports evaluating the efficacy of 23 JEV vaccines in swine based on challenge studies. The results of the efficacious vaccines (n = 16), from 16 reports, are summarized in Table 2.7. The types of vaccines evaluated included live attenuated, killed, and other types such as recombinant, chimeric, and virus-like particles. Four reports described comparisons of the efficacy of multiple vaccine types, and a single report detailed the results of a passive immunization with monoclonal antibodies (Young et al., 2020).

Six reports described challenges from natural exposure, while the remaining 13 challenges were conducted in a laboratory setting. The genotypes used for the laboratory challenges were GI (n = 3 reports), GIII (n = 6 reports), and unknown (n = 4 reports). Only two reports evaluated cross-protection between multiple genotypes. Fan et al. (2013) reported limited cross-protection of a vaccine derived from the GIII genotype against a GI challenge strain; Fan et al. (2018) reported that pigs vaccinated twice with a GI JEV virus-like particles vaccine had neutralizing antibodies against both GI and GIII JEV, with the GI antibody titer being almost 2x higher.

Sixteen vaccines were reported by the authors to be efficacious (live attenuated = 8, killed = 3, other = 5). Seven vaccines had inconclusive efficacy results (live attenuated = 2, killed = 3, other = 2), and one killed vaccine was reported as not efficacious. Fujisaki et al. (1975) found their live attenuated S-strain vaccine to be efficacious in finishing-aged Landrace pigs after vaccination and a booster, though its efficacy was inconclusive in finishing-aged Landrace and growing-aged research pigs after a single vaccination (no booster). However, they also reported that this vaccine was efficacious in mature, female, Landrace pigs after a single vaccination. Nine additional reports described the use of a JEV vaccine in swine, but failed to meet the inclusion criteria for the summary table, as the vaccinated pigs were not challenged with JEV (Sheng et al., 2016; De Wispelaere et al., 2015; Xu et al., 2011; Fei-fei et al., 2008; Xu et al., 2004; Nam et al., 2002; Konishi et al., 2000; Ogata et al., 1971; Yang et al., 2022). Authors in two of these reports indicated that disease challenge studies were not permitted at their institution (Sheng et al., 2016; De Wispelaere et al., 2015).

Commercially available vaccines were utilized in the studies from nine reports, but only five of these reports identified the vaccine manufacturer. Four reports indicated that the vaccine used was for veterinary use, though only Ueba et al. (1972) specified the manufacturer (tradename). Imoto et al. (2010) used a partial dose of a human-approved vaccine (JEVAX; Takeda Pharmaceutical Osaka, Japan), but no other tradenames were provided.

Basic reproduction ratio

Ten reports used mathematical equations and/or compartment models to describe JEV transmission and the results are summarized in Supplementary Table S8. However, only six of the 10 reports presented the basic reproduction ratio (R_0) for JEV incorporated in swine as hosts, under specific modes of transmission (i.e., vector-borne and/or pig-to-pig) and different control

strategies/scenarios (Table 2.8). All reports modeled vector-borne transmission routes; whereas only two reports included direct transmission (i.e., pig-to-pig), in addition to vector-borne transmission in their models, with the objective of modeling the contribution of direct transmission to the JEV epidemiological cycle in Cambodia (Diallo et al., 2018) or assessing the mechanism behind the JEV skip-and-resurgence patterns from 2003 to 2017 in Hong Kong (Zhao et al., 2018).

Most of the reports ($n = 5$) evaluated different control strategies, primarily human and swine vaccination and mosquito control, with the goal of controlling disease in human populations. Only one report explicitly modeled the transmission of JEV in feral pigs using various bird migration parameters and mosquito vectorial capacities, however researchers did not report R_0 ; this is the only report that modeled the transmission of JEV in the United States (Riad et al., 2017). All other reports modeled transmission in endemic or epidemic areas, specifically in Bangladesh, Cambodia, Hong Kong, India, Indonesia, and Japan.

For JEV R_0 in domestic swine derived from vector-borne transmission scenarios, the range of effect sizes was very wide. However, given the specificity of R_0 to the parameters and scenarios modeled, it is difficult to evaluate the consistency of these reports collectively. Yet, we were able to identify two knowledge gaps specific to JEV R_0 : a lack of reports evaluating R_0 in domestic swine from direct transmission scenarios, and a lack of reports evaluating R_0 in feral swine under any transmission scenarios.

Biosecurity

Only one study evaluating biosecurity measures was identified. Dutta et al. (2011) evaluated the effect of insecticide treated mosquito net placement (i.e., covering only human beds, only pig pens, human beds and pig pens, or no nets at all) on JEV seroconversion in mature

domestic pigs. In this study authors reported that covering pig pens alone or both pig pens and human beds with insecticide treated mosquito nets significantly reduced the relative risk of JEV seroconversion in pigs. Given the single study on the use of insecticide treated mosquito nets as a biosecurity intervention, the use and efficacy of this and other biosecurity measures to reduce JEV transmission in domestic swine is a knowledge gap.

Pork products

No reports on JEV detection in processed pork or pork products, or transmission from raw by-products, were obtained through our search. The lack of literature evaluating or discussing the risk of JEV detection in, or transmission through processed pork or pork products is a critical knowledge gap for understanding introduction routes and economic impacts, when considering pork products derived from JEV-infected animals.

Discussion

In this review, we synthesized published literature on the role of domestic and feral swine in JEV transmission and identified knowledge gaps. Whereas swine have been questioned as key contributors to JEV amplification in some regions where their removal did not alter broader transmission dynamics (van den Hurk et al., 2008), their involvement in the JEV cycle remains critical due to their capacity to maintain high levels of viremia and the resulting socioeconomic implications of JEV outbreaks in swine herds. Analyzing the epidemiological features of JEV in the context of swine populations provides crucial insights into transmission dynamics that directly impact human health and economic stability. The unveiling of knowledge gaps from this synthesis can assist stakeholders with research prioritization, enhance preparedness, and develop countermeasures to mitigate the impact of JEV outbreaks on public health and the swine industry.

Transmission routes

Research has shown that JEV can be transmitted to pigs through either vertical or horizontal routes (both indirectly by mosquito vectors and potentially by direct contact). Transmission to swine primarily occurs after a pig is bitten by an infected mosquito. Although this vector-mediated transmission route (horizontal, indirect) of JEV is well described in the literature, and remains the most commonly reported means of transmission, evidence of direct vector-free transmission, described by Ricklin et al. (2016a), prompted a reevaluation of the role of swine in the JEV transmission cycle. Vertical transmission from infected sows to their offspring has been reported, although it is also considered a less common route compared to mosquito-borne transmission. Furthermore, despite the detection of JEV in swine semen (Ogasa et al., 1977; Teng et al., 2013; Wu et al., 2017; Xiao et al., 2018), neither experimental nor observational evaluation of JEV transmission through artificial insemination was described in any of the reports identified in this review.

Once infected, domestic and feral swine can serve as amplifying hosts, typically experiencing viral titers of 10^4 infectious units per mL, viremia levels described as sufficient for transmission to mosquito vectors (Scherer et al., 1959; Sasaki et al., 1982; Takashima et al., 1988; Imoto et al., 2010; cited by Ladreyt et al., 2019). The viremia period for JEV in pigs has been reported to start as soon as 1 day post infection (Ricklin et al., 2016a), and the duration of the viremia window varies depending on the route of infection, dose of inoculum, and the viral strain. In subcutaneously challenged pigs, viremia has been reported to last anywhere from 1 to 8 days (Sazawa et al., 1969a; Yoshida et al., 1981; Ricklin et al., 2016a; García-Nicolás et al., 2017) and from 2 to 4 days following natural infection (Williams et al., 2001). Evidence of differences in the length of viremia among different genotypes, which could provide a fitness

advantage for transmission, was not directly evaluated during this review. An evaluation of the onset, duration, and magnitude of viral titers enabling a comparison among genotypes warrants a comprehensive meta-analysis.

Researchers have reported that JEV can remain detectable in the tonsils of swine for over 21 days post infection (Ricklin et al., 2016a, 2016b; Park et al., 2018; Redant et al., 2022), a period 5x longer than the average 4-day viremia period. However, the implications of this persistence in tonsils and the subsequent impact on transmission are poorly understood. Although JEV latency and reactivation has been demonstrated in mice (Mathur et al., 1986), this process has yet to be described regarding the persistent JEV in swine tonsils.

Pathological lesions, viral organotropism, and clinical signs

Japanese encephalitis virus infection can be clinically identified in swine herds when reproductive disorders are present in adults, including fetal abnormalities (mummified and stillborn fetuses) and abortions in sows, or by observing neurological signs in young animals. The similarity of JEV clinical manifestations to other endemic viruses, such as the porcine circovirus type 2 (PCV-2) or porcine reproductive and respiratory syndrome virus (PRRSV), presents a potential challenge for early disease detection in the event of a JEV incursion in the United States.

Despite reproductive clinical signs being well reported for sows, a lack of reports describing clinical signs in mature boars constitutes a knowledge gap in this area. Notably, JEV detection in the semen and “testicular fluid” of boars manifesting swollen testicles was reported in Teng et al. (2013) and Nie et al. (2022), respectively. Both studies used convenience samples based on abnormal clinical signs, and thus were not included in the clinical sign synthesis table of this review. However, these potential clinical signs warrant further investigation.

Our review added new evidence to the topic of macro- and microscopic lesions to what it has been previously summarized (Ladreyt et al., 2019) and compared differences in pathological lesions and viral organotropism within systems or organs, between JEV genotypes and study subject demographics; however, available published information was limited to genotypes I and III. Pathological lesions and organotropism were predominantly observed in the central nervous, lymphatic, and reproductive systems, with multiple other systems also affected. An especially intriguing aspect is the involvement of the olfactory bulb as a site for JEV infection. The potential for the olfactory bulb or other structures implicated in organotropic findings to serve as primary entry points into the central nervous system during non-vector transmission remains unclear, but it raises important questions about their role in altering the progression of the infection.

Although we did not identify any reports describing pathological lesions and organotropism of JEV in feral swine populations at the time of our search, a recent study conducted in Sinclair miniature pigs with a feral phenotype observed pathological outcomes consistent with those found in domestic swine after intradermal inoculation with genotype Ib (Park et al., 2023).

Diagnostic tests

Our review presents a detailed compilation of diagnostic tests evaluated or used for the detection of JEV in swine up to August 2022. Based on our findings, molecular tests, including RT-PCR assays, varied substantially in their diagnostic sensitivity and specificity estimates when detecting JEV in swine-derived samples. However, these assays exhibited high analytical sensitivity and specificity compared to alternatives such as viral antigen capture, or agglutination assays. When Williams et al. (2001) investigated the effect of prior exposure to Murray Valley

encephalitis and Kunjin viruses on levels of neutralization and monoclonal antibodies against JEV, via microtiter serum neutralization test and a series of blocking enzyme-linked immunosorbent assay (B-ELISA) tests, serologic cross-reaction of swine antibodies was observed, leading the authors to conclude that these diagnostic tests were inadequate for JEV surveillance in areas where other related flaviviruses are present. More recently, Chan et al. (2022) recognized that the broad antigenic cross-reactivity of antibodies to flaviviruses, specifically Dengue viruses, Zika virus, West Nile virus, and JEV, poses a challenge in interpreting serological results in regions where multiple flaviviruses are endemic. Despite these limitations among serological assays, including neutralization tests, enzyme-linked immunosorbent assay, hemagglutination-inhibition test, Western blot, and immunofluorescence test, neutralization tests are still considered the gold standard to differentiate these flaviviruses (Chan et al., 2022; World Organisation for Animal Health, 2023).

Currently, the proposed draft of the U.S. Disease Response Strategy: Japanese Encephalitis (United States Department of Agriculture - Animal and Plant Health Inspection Service (APHIS), 2023) references the intention to implement no-cost diagnostic testing for clinically affected animals as an initial outbreak response measure. The National Veterinary Services Laboratories, Foreign Animal Disease Diagnostic Laboratory, plans to use a reverse transcription-quantitative polymerase chain reaction (RT-qPCR) assay capable of detecting JEV genotypes I-IV, as well as sequencing methods for identification and confirmation of JEV in suspect samples. As the United States advances its strategies for disease response and preparedness concerning JEV, including surveillance and diagnostic testing infrastructure, it is imperative to address issues of cross-reactivity and test capacity. Furthermore, additional information regarding testing throughput and cost estimates would significantly benefit decision-

makers as they develop response strategies and evaluate diagnostic alternatives. Portable, rapid diagnostic tests are becoming essential tools for quick, cost-effective, on-site diagnosis, particularly in remote or resource-limited settings (Mohsin et al., 2022). As diagnostic technologies advance, these portable assays can offer significant improvements in JEV surveillance. For instance, Roberts et al. (2022) developed a portable sandwich-type lateral flow assay for detecting JEV in pig serum on-site, whereas You et al. (2024) introduced a portable one-pot RPA-EsCas13d detection system for rapid field detection of JEV. These tools are especially valuable in swine farms, where early detection is crucial to prevent virus spread. To keep recommendations relevant and accurate, future reviews incorporating more recent advancements, particularly those published post-2022, are necessary to provide up-to-date guidance for JEV detection in both endemic and at-risk areas.

Seroprevalence

Serosurveys from endemic countries provide valuable insights into annual disease epidemic patterns. Ladreyt et al. (2019) reported a thorough overview of epidemiological patterns of JEV seroprevalence in swine, encompassing both domestic and feral populations, from 16 of the 25 countries where JEV has been identified. Although these data are specific to the climate and geographical regions of collection, their patterns can be studied and compared to those observed for other closely related flaviviruses present in the United States, such as WNV (Johnson et al., 2015; Kretschmer et al., 2023), to predict JEV behavior and prepare for an incursion. However, predictions based on data from past climate patterns may be unreliable in the face of ongoing climate changes and its effects on disease dynamics. To support reliable prediction, an up-to-date repository for surveillance data on these epidemiologically complex diseases would not only support research endeavors in monitoring endemic flaviviruses in the

United States, but also facilitate contemporary understanding of mosquito population dynamics. This, in turn, would provide a foundation for the creation of efficient preparedness and intervention plans in the event of a JEV introduction to the United States.

Risk factors

Swine demographic risk factors

There was no evidence of a significant association between breed or sex with JEV seroprevalence. However, older pigs were consistently reported to have greater odds of being seropositive for JEV compared to younger animals. Based on seroprevalence alone, it is not possible to conclude whether this is due to a higher likelihood of exposure over their longer lifespan or an actual greater susceptibility to infection. This ambiguity is a result of utilizing JEV seroprevalence as the outcome measure, which describes a static state of seropositivity in a specific population but lacks the temporal aspect of disease onset. Seroprevalence was the primary outcome utilized in reports evaluating demographic risk factors in both domestic and feral swine. Incidence rate, often preferred for evaluating risk factors in epidemiological studies because it provides a time-specific measure of new cases in the population at risk, was not described in any of the reports included in this review regarding demographic risk factors (i.e., sex, breed, and age).

Swine operation risk factors

When investigating environmental risk factors for JEV seropositivity in swine, our review summarized available literature from regions where JEV is present. The small number of reports evaluating environmental risk factors limits our understanding of those risk factors to the specific swine production settings represented in these studies. Furthermore, the applicability or extrapolation of findings to the United States swine production system is limited due to the

complex interaction of environmental factors impacting JEV infection risk for a particular geographic location.

Reports describing studies specifically designed to evaluate farm risk factors associated with JEV infection in swine herds were limited. Additionally, incomplete or inconsistent reporting of results, including statistical significance, and unclear reporting of comparison groups or study design hindered our ability to draw meaningful conclusions about these risk factors. Lee et al. (2020), Lindahl et al. (2013), and Di Francesco et al. (2018) reported outcome values descriptively rather than analytically. Zhou et al. (2019) focused on validating a new diagnostic test for detection of JEV in swine-derived samples, and although samples were collected from swine groups at farms with different production stages, results were not reported or compared among these groups. Yamanaka et al. (2010) aimed to evaluate the association of pig density on two islands with JEV seroprevalence in swine farms, however, sampling was performed during the rainy season on one island and the dry season on the other, biasing their estimations.

Furthermore, reports in which seroprevalence or related outcomes in swine populations located in areas with varying levels of JEV risk were evaluated often did not explicitly discuss or describe these intrinsic characteristics and differences among study groups; therefore, comparative outcomes could not be extracted. Consequently, these reports were not included in the synthesis process.

Lastly, of the swine operation risk factors included in our synthesis, most were evaluated in only one study, except for swine housing type, which was evaluated by two different studies. The four reports summarized in this knowledge synthesis used a proportion of pigs that were JEV seropositive out of the total number of pigs at risk of JEV exposure as the outcome measure,

which, as previously discussed, only depicts a static state of disease in a particular study population. Additional studies investigating the association between environmental risk factors and JEV infection in swine, via seroprevalence or other outcome measures, would not only strengthen the body of evidence supporting previously identified farm-level risk factors, but also help identify additional risk factors relevant to other production systems.

Surveillance

Given the recent expansion of JE's geographic range throughout the Australian mainland, the World Health Organization (WHO) has recognized the need for strengthened surveillance efforts to assess the disease burden (World Organisation for Animal Health, 2022). Effective surveillance systems are crucial for timely detection of diseases, maximizing the efficiency of response efforts in resource-constrained environments. However, no reports evaluating the effectiveness of surveillance strategies in relation to swine, were identified in this review. Because swine species are considered amplifying hosts for JEV, their use as sentinels is not ideal for indicating the presence of JEV activity. High cost, ambiguous serology caused by cross-reacting antibodies to other flaviviruses, occupational risk associated with swine blood sampling, and increased public health risk of JEV transmission when sentinel pigs become viremic were highlighted as major disadvantages for the use of sentinel pigs (Ritchie et al., 2007). Testing feral swine during the hunting season has been also proposed as a monitoring strategy for JEV endemic areas, though the effectiveness of this approach has not been demonstrated (Nidaira et al., 2014).

Reports evaluating strategies in other species, and their potential effectiveness, although not covered in this review, are available. Mackenzie et al. (2022) described the JEV surveillance strategies in mainland Australia, prior to JEV GIV emergence and spread, which ultimately

failed to provide early evidence of JEV activity. These surveillance measures included testing of sentinel chickens and field-caught mosquitoes, combined with predictive modeling of climatic conditions (Mackenzie et al., 2022). Furthermore, although Mackenzie et al. (2022) did not address the effectiveness of surveillance systems, previous literature was contrasted to present a comprehensive discussion of the pros and cons regarding the effectiveness and costs of swine-alternative species—such as chickens, cattle, goats, dogs, and field-caught mosquitoes—for use in animal sentinel systems. Monath (2023) also discussed the recent JEV outbreak in Australia and speculated that JEV had likely spread southwards undetected in birds, feral pigs, and potentially bat populations for months before being detected in commercial pig farms located in southern Australia. A similar scenario could occur in other countries suitable for an incursion and lacking an active JEV surveillance system. Experts suggest that should a JEV epidemic occur in the United States, as it did in mainland Australia, abortion storms in swine could serve as the initial indicator of the disease. However, due to the clinical resemblance to other endemic swine diseases, recognition of a foreign animal disease may be delayed. Diagnostic challenges for a similar flaviviral incursion occurred during the emergence of West Nile virus (WNV) in the United States, resulting in delayed diagnosis and subsequent nationwide spread. Crucially, the introduction of WNV underscored the need for having robust surveillance and response systems in place to effectively manage emerging mosquito-vectored flaviviral diseases.

Currently, there is no active surveillance program for JE in the United States. Environmental surveillance strategies exist for WNV and include mosquito trapping and testing, live bird serology, and testing of horses and other vertebrate hosts. Specifically, the National Arboviral Surveillance System (ArboNET), managed by the Centers for Disease Control and Prevention [Center for Disease Control and Prevention (CDC), 2022], detects seasonal epidemics

of WNV. State health departments primarily report human cases, but ArboNET also collects data on arboviral infections from mosquitoes, dead birds, and sentinel animals. Despite its utility, ArboNET has significant limitations due to passive reporting and inconsistent surveillance investment among states, resulting in incomplete data, delayed reports, and underreporting. Since JEV and WNV are transmitted by similar mosquito species and infect comparable hosts, integrating JEV surveillance into existing WNV activities could be feasible but would face the same challenges if reliant on ArboNET.

Vaccine efficacy

Vaccines exist locally and are used in swine vaccination programs in JEV-endemic countries, including Japan, Korea, Nepal, Taiwan, and China, to protect sows from reproductive disorders. Most vaccines, inactivated and live-attenuated, are derived from cell cultures and are based on GIII, raising concerns about efficacy against other genotypes, such as IV and V. Vaccinating the breeding stock before the mosquito season starts can control viral amplification and reproductive disease in swine. The high turnover of market pig populations, maternal antibody interference, short time window for administration, genotype shifts, and logistic and budgetary constraints, may explain the low vaccination uptake and the slow progress in the development of JEV veterinary vaccines (Williams et al., 2019). Furthermore, pig immunization, along with mosquito mitigation, and human immunization and treatment have been evaluated using mathematical compartmental models. While each control measure contributed toward the reduction of JEV transmission, in most models, vaccination alone (of humans or pigs) was sub-optimally effective in reducing the number of infected pigs and thereby decreasing transmission (De et al., 2016; Kharismawati et al., 2019; Goswami, 2022).

While our review offers a comprehensive summary of the available information regarding efficacy of swine vaccines, a significant gap exists regarding the accessibility and licensure status of these vaccines for swine. There are currently no approved JEV vaccines for use in swine in the United States (United States Department of Agriculture - Animal and Plant Health Inspection Service (APHIS), 2023). Therefore, it seems imperative for the United States to have a plan for the rapid approval of swine vaccines in case of a JEV incursion. In its current draft form (United States Department of Agriculture - Animal and Plant Health Inspection Service (APHIS), 2023), the disease response strategy for JE states “if JE was identified in the U.S., APHIS would investigate availability of acceptable vaccines, potentially involving emergency approval of vaccines being used in other countries.” Identifying effective vaccines that can prevent JEV infection or impede transmission among swine, adopting specific emergency approval procedures, and securing emergency supply contracts, are critical for the responsible authorities to establish a rapid response in the event of a JEV outbreak.

Basic reproduction ratio

A key epidemiological metric used to describe transmissibility of infectious diseases, the basic reproduction ratio (R_0), represents the average number of secondary infections produced by a single infected individual in a completely susceptible population. Values for R_0 greater than one can lead to an epidemic as on average each infected host will infect more than one other host, whereas with R_0 less than one, the disease will decline and die out in the population. Most studies reported R_0 estimates for vector-borne transmission greater than one but ranged between –1.00 and 2.90. When pig-to-pig transmission was considered, R_0 was less than one, ranging from 0.001 to 0.83, indicating that direct transmission alone is insufficient to cause an epidemic. In Diallo et al. (2018), the direct transmission among swine populations accounted for up to

11.9% of the overall R_0 . While it may contribute to the epidemic's magnitude, it is unlikely to sustain transmission among pigs as effectively as the vector-borne route (Zhao et al., 2018). Thus far, these findings support the conclusion that mosquito-mediated transmission remains the most efficient method for disease spread.

Previously overlooked in prior reviews, this parameter provides crucial information for modeling the transmission and spread of JEV in the United States. However, R_0 is not a fixed value and is dependent on factors modeled, such as host availability, mosquito abundance and survival, biting rates, and the incubation period of the virus within the mosquito vector. Given the limited number of models and their geographical/management settings (i.e., Bangladesh, Cambodia, India, Indonesia, and Hong Kong), more work needs to be done in this area to expand the usability of these models to other areas.

Biosecurity

In addition to vaccination, the implementation of biosecurity measures can contribute to the prevention of viral exposure and infection. Only one report evaluating biosecurity measures, specifically the use of insecticide-treated mosquito nets in pig pens, was identified and included in this review (Dutta et al., 2011). The scarcity of information regarding the evaluation of biosecurity interventions may be attributed to the swine-specific search terms used in this review. Consequently, unless the records explicitly referenced swine, they were not considered, potentially overlooking strategies only targeting mosquito vectors. This lack of information hinders the formulation of evidence-based recommendations on key biosecurity measures, including but not limited to vector control, quarantine, the safe introduction of replacement animals, and low-risk movements of people, animals, and vehicles within swine production systems. Other conventional biosecurity strategies typically employed in commercial swine

production systems, such as air filtration, cleaning and disinfection of barns, vehicles, and fomites, as well as perimeter fencing, remain to be evaluated in the context of JEV transmission.

Current biosecurity recommendations for United States swine farms prioritize the prevention of endemic, and some foreign animal diseases like African Swine Fever, Classical Swine Fever, and Foot and Mouth Disease (Secure Pork Supply, 2017). These practices address the primary transmission pathways for those diseases, which include direct contact, mechanical vectors (fomites), aerosols, and contaminated feed. While these programs encompass a range of strategies, including environmental management, the establishment of physical barriers, and the application of chemical and biological controls, to mitigate the risk of disease transmission via insect vectors and wildlife, the recommendations may not be sufficiently robust to prevent diseases where mosquito vectors are the primary route of transmission (Secure Pork Supply, 2017; Alarcón et al., 2021).

Pork products and other disease impacts

To date, no import or export restrictions have been imposed on JEV positive herds or countries. Recently, messaging from Australia has emphasized that JE is not a food safety concern (Business Queensland, 2023). This messaging is also included in the preliminary draft of the United States Disease Response Strategy for JEV (United States Department of Agriculture - Animal and Plant Health Inspection Service (APHIS), 2023). However, our search yielded no reports pertaining to the safety of processed pork and pork by-products to provide definitive support for these statements. The poor environmental stability described for JEV and other related flaviviruses, such as Zika virus, which are sensitive to UV and gamma radiation, heat, extreme pH, and various chemical disinfectants (Müller et al., 2016; Williams et al., 2019; World Organisation for Animal Health, 2019) suggests that JEV is unlikely to survive in pork products.

However, publishing literature addressing the safety of pork products originating from JEV-endemic regions is pivotal for informing public health and food safety policies and recommendations.

Although not initially among our primary research questions, economic impact was identified by experts and stakeholders as a critical outcome of interest. However, given its indirect relationship to JEV transmission, our overarching theme, we deemed it to be a secondary topic of interest. While production losses associated with abortion in sows and infertility in boars, and additional costs related to control and prevention for JEV are expected, studies quantifying the economic impact of JEV introduction into swine production systems are scarce. Although, no peer-reviewed reports evaluating the economic impact of JEV within the context of swine production systems were identified in this review, a recently published economic assessment exploring the potential impacts of a JEV incursion in the United States reported that an estimated 32% of the total United States breeding herd (2,135,940 sows) would be impacted, resulting in a 1 to 2% reduction in United States pork production output, and an estimated economic loss to the United States pork industry ranging between USD 306 million and USD 612 million (Hayes et al., 2024).

Study design and limitations

Systematic reviews, which are designed to minimize bias, employ explicit methods for conducting a comprehensive literature search, assessing eligibility, and critically appraising study quality. Scoping reviews map the literature by extent, time range, and nature of existing research on a particular topic. This review combined traits from both systematic and scoping reviews to comprehensively explore overall themes pertaining to the role of swine in the transmission of JEV and its effects on swine production systems, particularly focusing on the

U.S. From our synthesis, we identified knowledge gaps in the understanding of the role of swine in JEV transmission. These knowledge gaps can inform United States research initiatives needed to improve our understanding of mechanisms of JEV introduction, transmission, and disease impacts, and aid in the development of preparedness efforts for a potential JEV incursion in the United States.

By design, rapid systematic reviews are a modified version of traditional systematic reviews. They incorporate methods to expedite the review process without compromising its systematicity, reproducibility, and transparency. By creating a protocol a priori and thoroughly documenting our methods using the PRISMA-P 2015 (Moher et al., 2015) and PRISMA 2020 (Page et al., 2021) checklists, we ensured a reproducible and transparent methodology. However, the necessary streamlining of a rapid process due to logistical and time constraints may result in some relevant studies being excluded. For example, as we only captured articles written in English, relevant literature, considering the Asian origin and distribution of this disease, was likely excluded. This limitation may have led to a biased selection of literature included for this review. Acknowledging this risk, the benefits of a systematic review completed in a shorter timeframe are more valuable to policymakers and stakeholders needing to make evidence-based decisions.

Conclusion

Pigs have a central role in the transmission cycle of JEV. They not only sustain transmission and facilitate spillover to other hosts by producing sufficient viremia to infect mosquito vectors, but they also can display clinical signs of reproductive and neurological disease. This review provides insights into the disease process dynamics, detection methods, control and preventive options, and potential impacts in the swine production system.

Most of the evidence suggests that domestic pigs may be pivotal in the transmission of JEV, while the relative importance of feral swine remains unclear. Research in feral swine is imperative for informing policymaking and the development of strategic initiatives aimed at mitigating JEV spread and surveilling viral activity. The estimated 6 million feral swine present in 35 U.S. states could serve as efficient hosts of JEV, should it be introduced. Improved knowledge regarding the dynamics of feral swine populations in the United States and their potential role in the spread and establishment of JEV, would be invaluable for assessing the risk posed to commercial swine operations located in various regions across the country.

Given the importance of the swine industry to the United States economy, a JEV incursion would cause a significant impact to this sector, considering the susceptible immune status of the United States pig population. Previous exposure to other flaviviruses (e.g., WNV) may confer some level of cross-protection to United States swine herds, however, the extent of this protection and its impact on JEV's basic reproduction ratio is not known. In the event of a JEV incursion in the United States, mathematical models will likely be used to inform policy decisions regarding its control, highlighting the importance of understanding dynamics of disease transmission and spread.

Having access to information for making evidence-based decisions is crucial for minimizing significant potential impacts on animal health and the economy within the swine sector. Once information is gathered, providing education to and encouraging communication between government officials, veterinarians, academics, and swine producers becomes critical. The consideration of existing evidence aids in the identification of research priorities by highlighting important areas where missing or inadequate information limits the ability of a researcher to reach a conclusion and make an evidence-based decision. This is particularly

crucial in the event of an outbreak in the United States, where preemptive measures can help minimize the spread of the virus, safeguard both human and animal populations, and ensure the long-term sustainability of the swine production sector.

Data Availability Statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author Contributions

VH: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Project administration, Conceptualization. CH: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. AD: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. SE: Writing – review & editing, Investigation. AT: Writing – review & editing, Investigation. DM: Writing – review & editing, Methodology, Investigation, Funding acquisition. LN: Writing – review & editing, Methodology, Investigation, Funding acquisition. LC: Writing – review & editing, Funding acquisition. VB: Writing – review & editing, Methodology, Resources. CM: Writing – review & editing, Funding acquisition. NC: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Project administration, Supervision, Funding acquisition, Conceptualization.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. Financial support was provided by the Swine Health

Information Center (SHIC Project ID 22-070), the Center for Outcomes Research and Epidemiology, and the College of Veterinary Medicine at Kansas State University.

Acknowledgments

We would like to express our gratitude to the following individuals for their contributions to this research including Madison Evje (ME), Taylor McAtee (TM), Shakirat Adetunji, John Ekakoro, and David Edache.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary Material

The Supplementary material for this article can be found online at:

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Tables and Figures

Table 2.1. Eligibility criteria for inclusion in the rapid systematic review on domestic and feral swine's role in the transmission of Japanese encephalitis virus (JEV)

Criteria	Description
Bibliographic databases	
Population (P)	Swine species (domestic (<i>Sus domesticus</i>) or feral (<i>Sus scrofa</i>)) of any age, sex, or breed
Outcome (O)	Any outcome related to JEV transmission in swine (i.e., JEV basic reproduction number (i.e., R_0), routes of transmission, viral and antibody titers in swine after exposure, duration of viremia, clinical signs and pathological findings, economic impacts at the farm level, JEV vaccine availability and efficacy, tests used to diagnose/identify JEV and their performance)
Study design (S)	No restriction
Language	English
Location	No restriction
Time period	No restriction
Type of evidence	Peer-reviewed articles
Other sources	
Population (P)	Feral swine (<i>Sus scrofa</i>) of all ages and sexes
Outcome (O)	Same as those described for the bibliographic databases
Study design (S)	No restriction
Language	English
Location	No restriction
Time period	No restriction
Type of evidence	No restriction

Table 2.2. Research questions, location of knowledge synthesis table and number of reports (N) identified and extracted per research question, and summary of knowledge gaps, identified as per Robinson et al. (2013), associated with each research question

Research question	Knowledge synthesis table (N)	Knowledge gap summary
Pathological lesions associated with JEV infection in swine	Supplemental Table S4 (16)	Pathological lesions associated with JEV genotype I were limited to the central nervous system of domestic swine. No reports describing pathological lesions associated with JEV genotypes II, IV, or V in domestic swine were identified. There were no reports describing pathological lesions associated with any JEV genotype in feral swine populations.
Viral organotropism associated with JEV infection in swine	Supplemental Table S4 (22)	There were no reports describing organotropism associated with JEV genotypes II, IV, or V in domestic swine, or any reports describing organotropism associated with any JEV genotype in feral swine.
Clinical signs associated with JEV infection in swine	Table 3 (26)	No reports describing clinical signs in feral swine were identified during this review. Small sample sizes, reporting deficiencies, and inconsistency in observed clinical signs were the most frequent limitations for drawing conclusions for specific age categories. There were no studies detailing clinical signs associated with JEV genotypes II, IV, or V in any swine population.
Diagnostic tests for JEV available for use in swine*	Supplemental Table S5 (211)	NA
Diagnostic tests for JEV evaluated in swine	Table 4 (28); Supplemental Table S6a,b (37)	NA
Demographic risk factors (breed, sex, age) for JEV infection in swine	Table 5 (13)	There was a limited number of studies evaluating the association between sex in domestic and feral swine, as well as age in feral swine with JEV seroprevalence (or seroconversion). Although increased age was consistently associated with higher JEV seroprevalence in domestic swine, there were few studies conducted in feral swine to draw conclusions and therefore this also remains a knowledge gap.
Farm-level risk factors for JEV infection in domestic swine	Table 6 (4)	The limited number of reports and uncertainty regarding the consistency of observed results were the main drivers of the knowledge gap associated with farm-level risk factors. Additionally, there was limited literature evaluating the association between environmental risk

		factors representative of those in U.S. swine production systems with JEV seroprevalence or seroconversion.
JEV surveillance strategies in swine	NA (0)	No reports evaluating the effectiveness of surveillance strategies for JEV in swine herds were identified.
JEV vaccine efficacy in swine	Table 7 (16); Supplemental Table S7 (19)	NA
JEV basic reproduction ratio (R_0) in swine populations	Table 8 (7); Supplemental Table S8 (10)	Reports estimating R_0 via vector-borne or direct transmission in domestic or feral pigs from observational data were not captured in this review. Similarly, reports evaluating R_0 via direct transmission from experimental data in feral pigs were not captured. Mathematical models estimating R_0 in the context of other eco-climates, besides tropical to sub-tropical, were not identified.
Biosecurity to prevent JEV infection in domestic swine	NA (1)	No other biosecurity measures, besides the use of insecticide-treated mosquito nets covering swine pens, were evaluated within reports included in this review.
JEV transmission via pork products	NA (0)	No reports evaluating JEV transmission via pork products were identified.

JEV = Japanese encephalitis virus; N = Number of reports addressing the corresponding research question and included in the respective summary tables; NA = Not applicable (indicated when no reports were identified regarding the research question, or the research question was not amenable for utilization of the knowledge gap tool).

* Among the 211 reports describing use of a diagnostic test for JEV detection in swine samples, 51 unique diagnostic tests were identified.

Table 2.3. Clinical signs associated with Japanese encephalitis virus (JEV) infection in swine from experimental and observational studies. Results are organized by clinical sign (alphabetical) and within sign by age and genotype (GI, GIII, unknown (UN)), and within sign by age and genotype (GI, GIII, unknown (UN)), and within genotype, alphabetically by strain and then inoculation route

Population [breed; sex]	Strain (Genotype)	Infection route	Dose	Affected / observed (%)	Reference(s)
<i>Anorexia</i>					
Nursing					
Other(research); NR	Fuji (GIII)	S	10 ⁷ TCID ₅₀	NR (> 0)	Sazawa, H. et al. (1969a)
	Sagara (UN)	S	10 ⁵ TCID ₅₀	NR (> 0)	
Weaning					
Large White; Both	Nakayama (GIII)	V/D	10 ⁷ TCID ₅₀	5/5 (100)	Ricklin, M.E. et al. (2016a)
				12/12 (100)	Ricklin, M.E. et al. (2016b)
Landrace; NR	Nakayama (GIII)	D	10 ⁵ TCID ₅₀	0/24 (0)	Redant, V. et al. (2020)
		N	10 ⁵ TCID ₅₀	0/24 (0)	
Finishing					
NR; NR	Okinawan (UN)	V	1mL of 10 ⁻² dilution of mouse brain suspension	3/3 (100)	Meiklejohn, G., Simpson, T.W., and Stacy, I.B. (1947)
<i>Central nervous system signs</i>					
Nursing					
Other(research); NR	Fuji (GIII)	C	10 ^{6.3} TCID ₅₀	NR (> 0)	Sazawa, H. et al. (1969a)
		N	10 ⁷ TCID ₅₀	NR (> 0)	
Unspecified; NR	Nakayama (GIII)	S	10 or 100 LD ₅₀	2/2 (100) [†]	Kodama, K., Saski, N., and Inoue, Y.K. (1968)
		S	10 LD ₅₀	1/1 (100)	
	Furumoto (UN)		100 LD ₅₀	0/1 (0)	
Other(research); NR	Sagara (UN)	N	10 ^{5.2} TCID ₅₀	NR (> 0)	Sazawa, H. et al. (1969a)
		C	10 ^{4.5} TCID ₅₀	NR (> 0)	
Weaning					
Other(research); NR	IB 2001 (GI)	N	2mL of 10 ⁶ TCID ₅₀ /mL	4/8 (50)	Yamada, M. et al. (2009)
		V	5mL of 10 ⁶ TCID ₅₀ /mL	3/6 (50)*	Yamada, M. et al. (2004)
Other; NR	JE-91 (GI)	V	1mL of 10 ⁷ TCID ₅₀ /mL	3/10 (30)	Park, S.L. et al. (2018)
Landrace; NR	Nakayama (GIII)	D	10 ⁵ TCID ₅₀	0/24 (0)	Redant, V. et al. (2020)
		N	10 ⁵ TCID ₅₀	0/24 (0)	

Other(research); NR	AS-6 (UN)	V	5mL of 10 ⁶ TCID ₅₀ /mL	6/6 (100) [*]	Yamada, M. et al. (2004)
Finishing					
NR; NR	Okinawan (UN)	V	1mL of 10 ⁻² dilution of mouse brain suspension	3/3 (100)	Meiklejohn, G., Simpson, T.W., and Stacy, I.B. (1947)
Conjunctivitis					
Finishing					
NR; NR	Okinawan (UN)	V	1mL of 10 ⁻² dilution of mouse brain suspension	3/3 (100)	Meiklejohn, G., Simpson, T.W., and Stacy, I.B. (1947)
Decreased fecal output					
Weaning					
Large White; Both	Nakayama (GIII)	A	NA	2/8 (25)	Ricklin, M.E. et al. (2016a)
		V/D	10 ⁷ TCID ₅₀	5/5 (100)	
		V/D	10 ⁷ TCID ₅₀	12/12 (100)	Ricklin, M.E. et al. (2016b)
Depression					
Nursing					
Unspecified; NR	Nakayama (GIII)	S	10 or 100 LD ₅₀	2/2 (100) [†]	Kodama, K., Saski, N., and Inoue, Y.K. (1968)
	Furumoto (UN)	S	10 or 100 LD ₅₀	2/2 (100) [†]	
NR; NR	NR	NE	NA	3/5 (60)	Burns, K.F. (1950)
Weaning					
Other(research); NR	IB 2001 (GI)	N	2mL of 10 ⁶ TCID ₅₀ /mL	4/8 (50)	Yamada, M. et al. (2009)
		V	5mL of 10 ⁶ TCID ₅₀ /mL	3/6 (50) [*]	Yamada, M. et al. (2004)
Other; NR	JE-91 (GI)	V	1mL of 10 ⁷ TCID ₅₀ /mL	10/10 (100)	Park, S.L. et al. (2018)
Large White; Both	Nakayama (GIII)	A	NA	2/8 (25)	Ricklin, M.E. et al. (2016a)
Landrace; NR	Nakayama (GIII)	D	10 ⁵ TCID ₅₀	0/24 (0)	Redant, V. et al. (2020)
		N	10 ⁵ TCID ₅₀	0/24 (0)	
Large White; Both	Nakayama (GIII)	V/D	10 ⁷ TCID ₅₀	5/5 (100)	Ricklin, M.E. et al. (2016a)
				12/12 (100)	Ricklin, M.E. et al. (2016b)
Other(research); NR	AS-6 (UN)	V	5mL of 10 ⁶ TCID ₅₀ /mL	6/6 (100) [*]	Yamada, M. et al. (2004)
Finishing					
NR; NR	Okinawan (UN)	V	1mL of 10 ⁻² dilution of mouse brain suspension	3/3 (100)	Meiklejohn, G., Simpson, T.W., and Stacy, I.B. (1947)
Fever					

Nursing					
Other(research); NR	Fuji (GIII)	S	10 ⁷ TCID ₅₀	NR (> 0)	Sazawa, H. et al. (1969a)
Unspecified; NR	Nakayama (GIII)	S	10 or 100 LD ₅₀	2/2 (100) [†]	Kodama, K., Sasaki, N., and Inoue, Y.K. (1968)
	Furumoto (UN)	S	10 or 100 LD ₅₀	2/2 (100) [†]	
Other(research); NR	Sagara (UN)	S	10 ⁵ TCID ₅₀	NR (> 0)	Sazawa, H. et al. (1969a)
Weaning					
Other(research); NR	IB 2001 (GI)	N	2mL of 10 ⁶ TCID ₅₀ /mL	8/8 (100)	Yamada, M. et al. (2009)
		V	5mL of 10 ⁶ TCID ₅₀ /mL	6/6 (100)*	Yamada, M. et al. (2004)
Other; NR	JE-91 (GI)	V	1mL of 10 ⁷ TCID ₅₀ /mL	NR/10 (> 0)	Park, S.L. et al. (2018)
Other(research); NR	YL2009-4 (GI)	S	10 ⁵ FFU	3/3 (100)	Fan, Y.-C. et al. (2018, 2019)
			10 ⁷ FFU	4/4 (100)	
	CH1392 (GIII)	S	10 ⁵ FFU	0/3 (0)	
			10 ⁷ FFU	4/4 (100)	
NR; NR	JaOH 0566 (GIII)	S	10 ^{7.4} PFU	1/1 (100)	Yoshida, Y. et al. (1981)
Large White; Both	Nakayama (GIII)	A	NA	4/8 (50)	Ricklin, M.E. et al. (2016a)
Landrace; NR	Nakayama (GIII)	D	10 ⁵ TCID ₅₀	NR/24 (> 0)	Redant, V. et al. (2020)
		N	10 ⁵ TCID ₅₀	NR/24 (> 0)	
Large White; Both	Nakayama (GIII)	V/D	10 ⁷ TCID ₅₀	5/5 (100)	Ricklin, M.E. et al. (2016a)
				12/12 (100)	Ricklin, M.E. et al. (2016b)
		O	10 ¹ , 10 ² , 10 ³ , 10 ⁵ , or 10 ⁷ TCID ₅₀	15/15 (100) [‡]	Ricklin, M.E. et al. (2016a)
Landrace; NR	Nakayama (GIII)	O	10 ⁷ TCID ₅₀	3/3 (100)	de Wispelaere, M. et al. (2015)
Other(research); NR	AS-6 (UN)	V	5mL of 10 ⁶ TCID ₅₀ /mL	6/6 (100)*	Yamada, M. et al. (2004)
Large White; Both	NJ2008 (UN)	V/D	2mL of 2 x 10 ⁷ TCID ₅₀	1/3 (33)	Xie, S. et al. (2022)
Finishing					
NR; NR	Okinawan (UN)	V	1mL of 10 ⁻² dilution of mouse brain suspension	3/3 (100)	Meiklejohn, G., Simpson, T.W., and Stacy, I.B. (1947)
Mature					

Yorkshire; Female	Kanagawa (GIII)	V	5mL of $10^{6.0}$, $10^{7.2}$, $10^{7.5}$, or $10^{8.5}$ LD ₅₀	1/6 (17)	Shimizu, T. et al. (1954)
<i>Reproductive failure</i>					
Mature					
Landrace and Other; Female	IVRI395A (GIII)	NE	NA	2/28 (7)	Desingu, P.A. et al. (2016)
Yorkshire/Landrace; Female	JaOH 0566 (GIII)	NR	$10^{7.9}$ PFU	2/2 (100)	Yoshida, Y. et al. (1981)
Yorkshire; Female	Kanagawa (GIII)	V	5mL of $10^{6.0}$, $10^{7.2}$, $10^{7.5}$, or $10^{8.5}$ LD ₅₀	5/6 (83)	Shimizu, T. et al. (1954)
NR; Female	SC201301 (GIII)	NE	NA	NR/200 (> 0)	Wu, R. et al. (2016)
Landrace; Female	AS-6 (UN)	S	10^7 TCID ₅₀	2/2 (100)	Fujisaki, Y. et al. (1975)
NR; Female	NR	NE	NA	13/213 (6)	Fan, Y.-C. et al. (2022)
Duroc, Landrace, Yorkshire, Hybrids, Other; Female	NR	NE	NA	4/211 (2)	Lindahl, J. et al. (2012)
NR; Female	NR	NE	NA	23/51 (45)	Lindahl, J.F. et al. (2013)
NR; Female	NR	NE	NA	7 farms affected/NR	Takashima, I. et al. (1988)
NR; Female	NR	NE	NA	11/NR	Higgins, D. (1970)
<i>Weight loss</i>					
Weaning					
Other; NR	JE-91 (GI)	V	1mL of 10^7 TCID ₅₀ /mL	10/10 (100)	Park, S.L. et al. (2018)
<i>Absence of clinical signs</i>					
Weaning					
Large White; Both	SA14-14-2 (GIII)	V/D	2mL of 2×10^7 TCID ₅₀	3/3 (100)	Xie, S. et al. (2022)
	rA66G (GIII)	V/D	2mL of 2×10^7 TCID ₅₀	3/3 (100)	
NR; NR	KV1899 (GI)	M	1mL of $10^{3.3}$ TCID ₅₀ /mL	10/10 (100)	Yang, D.K. et al. (2004a)
Weaning to Finishing					
NR; NR	NR	NE	NA	29/29 (100)	Cappelle, J. et al. (2016)
Mature					
Yorkshire; Female	Fuji (UN)	V	5mL of $10^{6.5}$, $10^{9.3}$, or $10^{9.5}$ LD ₅₀	5/5 (100)	Shimizu, T. et al. (1954)

A = Aerosol; C = Intracerebral; D = Intradermal; M = Intramuscular; N = Nasal; NE = Natural exposure; NR = Not reported; O = Oronasal; S = Subcutaneous; V = intravenous.

FFU = Focus-forming unit; PFU = Plaque forming unit; LD₅₀ = Dose of JEV that is sufficient to kill 50% of test mice inoculated intracerebrally; TCID₅₀ = Tissue culture infection dose (50%); NA = Not applicable.

*Three pigs were euthanized and necropsied at three days post-infection and the other three pigs at seven days post-infection.

† Sample size is one pig at each dose.

‡ Sample size is three pigs at each dose.

Table 2.4. Diagnostic sensitivity and specificity of diagnostic tests evaluated against a reference test for the detection of Japanese encephalitis virus (JEV) and JEV antibodies

Test name	Sample type	Reference test	Sensitivity	Specificity	Reference(s)
<i>Detection of virus</i>					
Antigen detection					
Immunochromatographic strip test	Tissue homogenate	RT-PCR	85.7%*	99.3%*	Li, Y. et al. (2010)
Immunochromatographic	Serum	IgG IF assay	84.8%	97.8%	Cha, G.-W. et al. (2015)
Molecular tests					
Bio-Plex 200	Multiple tissues/Fluids	PCR/RT-PCR	62.5%*	NR	Xiao, L. et al. (2018)
EvaGreen-based multiplex real-time PCR	Multiple tissues/Serum	PCR	No samples tested positive for JEV		Rao, P. et al. (2014)
GenomeLab Gene Expression Profiler analyser-based multiplex PCR	Multiple tissues	Single RT-PCR/real-time PCR	100.0%*	100.0%*	Zhang, M. et al. (2015)
Multiplex ligation-dependent probe amplification	Blood	Real-time PCR	No samples tested positive for JEV		Zhou, Y. et al. (2020)
Multiplex real-time PCR	Multiple tissues/Serum	Singleplex real-time PCR	No samples tested positive for JEV		Wu, H. et al. (2014)
Multiplex RT-PCR	Multiple tissues	Virus isolation	66.7%	NR	Chen, H.-Y. et al. (2010)
RT-LAMP	Blood	RT-PCR Real time RT-PCR	See Table 4 in ref for more information		Liu, H. et al. (2012)
RT-LAMP	Serum	RT-PCR	87.0%	99.0%	Tian, C.J. et al. (2012)
RT-LAMP	Blood	Real time RT-PCR [†]	100.0%	100.0%	Dhanze, H. et al. (2015)
RT-PCR	Blood	Real time RT-PCR [†]	25.0%	100.0%	
<i>Antibody detection</i>					
Enzyme-linked immunoassays (ELISA)					
Blocking ELISA	Serum	Indirect ELISA	See Table 2 and ref for specifics		Zhou, D. et al. (2019)
Biotin-labeled protein-A ELISA	Serum	HI	98.1%	98.5%	Chang, H.-C. et al. (1984b)
Biotin-labeled antigen sandwich enzyme-linked immunosorbent assay	Serum	HI and labeled avidin-biotin-ELISA IgM	Comparisons at multiple time points		Chang, H.-C. et al. (1984a)
ELISA Aceton-ether zonal antigen	Serum	HI	91.7%*	97.2%*	

ELISA sucrose-aceton antigen	Serum	HI	100.0%*	16.9%*	Ohkubo, Y. et al. (1984)
ELISA-IgG	Serum	HI	93.3%*	100.0%*	Yamaoka, M. (1983)
ELISA-IgM	Serum	HI	82.9%*	93.7%*	Yamaoka, M., Konishi, E., and Matsumura, T. (1982)
Indirect ELISA	Serum	HI	83.6%*	89.5%*	Xinglin, J. et al. (2005)
Indirect ELISA	Serum	HI	94.3%*	81.5%*	Yang, D.-K. et al. (2006)
		Serum neutralization	93.7%*	81.0%*	
Indirect ELISA	Serum	HI	92.2%*	91.8%*	Yang, D.-K. et al. (2017)
		PRNT ₉₀	98.6%*	95.0%*	
		VNT	98.7%*	95.0%*	
Indirect ELISA IgG	Serum	VNT	82.8%*	78.9%*	Kohle, R.P. et al. (2015)
Indirect ELISA IgM	Serum	VNT	62.8%*	81.6%*	
Recombinant NS1 protein based dipstick IgG ELISA	Serum	Indirect IgG ELISA	100.0%*	92.9%*	Chauhan, J. et al. (2020)
Recombinant NS1 protein based indirect IgG ELISA	Serum	VNT	91.0%	97.0%	Dhanze, H. et al. (2019)
Recombinant NS1 protein based indirect IgM ELISA	Serum	VNT	90.6%*	81.8%*	Dhanze, H. et al. (2020b)
		IgM ELISA	95.3%*	98.6%*	
Other					
Lateral flow assay (format I)	Serum	Indirect IgG ELISA	Authors determined not suitable for JEV antibody screening		Dhanze, H. et al. (2020a)
Lateral flow assay (format II) [‡]	Serum	Indirect IgG ELISA	55.7%	100.0%	
Lateral flow assay (format III)	Serum	Lateral flow assay (format II)	25.6%	100.0%	
Latex agglutination test	Serum	HI	91.7%	NR	Xinglin, J. et al. (2002)
Latex agglutination test	Serum	IgG ELISA	80.2%	95.2%	Grace, M.R. et al. (2019b)
Latex agglutination test	Serum	VNT	82.2%*	87.8%*	Grace, M.R. et al. (2019a)

HI = Haemagglutination inhibition; IF = Immunofluorescence; NR = Not reported; NS = Non-structural; PCR =

Polymerase chain reaction; PRNT = Plaque reduction neutralization test; qPCR = Quantitative-polymerase chain reaction;

RT-LAMP = Reverse transcriptase loop-mediated isothermal amplification; RT-PCR = Reverse-transcriptase polymerase chain reaction; VNT = Virus neutralization test.

*Reviewer calculated.

†Real time RT-PCR was developed by authors and used as reference for RT-LAMP and RT-PCR.

‡100% sensitivity and specificity reported in subset of samples collected during monsoon and post-monsoon season.

Table 2.5. Results from observational studies examining associations between population demographics (breed, sex, and age) and Japanese encephalitis virus (JEV) seropositivity in swine, including the number of reports that evaluated each risk factor, risk factor levels, population description, sample size, model-adjusted seroprevalence or odds ratio for JEV positivity, statistical significance of differences, and respective references

Population*	Location	Risk factor level	Positive/ Total (%)	Seroprevalence, % (95% CI)	Odds ratio (95% CI)	P-value	Reference(s)
<i>Breed (n = 5)</i>	<i>Summary: No evidence of an association between breed and JEV seroprevalence in domestic swine.</i>						
Domestic							
Both; Finisher to mature	Nepal	Local	10/152 (6.6)	-	REF	< 0.15 [§] but > 0.05 [‡]	Thakur, K.K. et al. (2012)
		Exotic Improved	5/83 (6.0)	-	0.9 (0.3-2.8) [§]		
		Mixed breed	61/219 (27.8)	-	5.5 (2.7-11.2) [§]		
Female; Mature	Vietnam	Duroc	NR/15	NR	NR	> 0.05 [§]	Lindahl, J. et al. (2012)
		Landrace	NR/28				
		Yorkshire	NR/164				
		Hybrids	NR/72				
NR; Finisher to mature	Laos	Wet: Indigenous	NR/191	80.6 (0.75-0.86)	-	Wet season: 0.89*	Conlan, J.V. et al. (2012)
		Wet: Exotic	NR/68	82.4 (73.1-91.6)	-		
		Wet: Crossbreed	NR/18	77.8 (56.5-99.1)	-		
		Dry: Indigenous	NR/367	70.6 (65.9-75.2)	-	Dry season: 0.89*	
		Dry: Exotic	NR/10	70.0 (35.4-100.0)	-		
		Dry: Crossbreed	NR/11	72.7 (41.3-100.0)	-		
Both; Young to mature	Malaysia	Local	NR/88 (43.2)	-	0.95 (0.9-1.0)	> 0.05*	Kumar, K. et al. (2018)

		Import	NR/2 (100.0)	-	REF		
Both; Grower to mature	Cambodia	Crossbreed	Total:	100.0 (NR)	-	0.38*	Henriksson, E. et al. (2021)
		Commercial	185/199 (93.0)	96.8 (NR)	-		
		Indigenous		91.0 (NR)	-		
Sex (n = 5)		Summary: No evidence of an association between sex and JEV seroprevalence in swine.					
Domestic							
Unspecified; Finisher to mature	Nepal	Female	45/226 (19.9)	-	REF	0.07§ but > 0.05‡	Thakur, K.K. et al. (2012)
		Male	31/228 (15.7)	-	0.6 (0.3-1.0)§		
NR; Weaner to finisher	Tibet	Female	11/194 (5.7)	5.7 (NR)	-	> 0.05*	Zhang, H. et al. (2017b)
		Male	12/260 (4.6)	4.6 (NR)	-		
Unspecified; Young to mature	Malaysia	Female	NR/20 (55.0)	-	1.5 (0.7-3.3)	> 0.05*	Kumar, K. et al. (2018)
		Male	NR/70 (41.4)	-	0.9 (0.7-1.1)		
Feral							
Juveniles and adults	Japan	Female	Total:	76.9 (NR)	-	> 0.05	Ohno, Y. et al. (2009)
		Male	30/36 (83.3)	87.0 (NR)	-		
Young and adults	Japan	Female	Total:	NR	NR	Not significant ⊥	Sugiyama, I. et al. (2009)
		Male	47/90 (52.2)				
Age (n = 10)		Summary: Most studies (n = 7 of 11) found a risk of increased swine JEV seroprevalence associated with increasing age; only one study found a significant, negative association.					
Domestic							
NR; NR	Thailand	4-6 mo.	44/65 (67.7)	NR	NR	0.04*	Burke, D.S. et al. (1985)
		7-12 mo.	30/35 (85.7)				
NR; NR	Cambodia	≤ 2 mo.	94/198 (47.5)	NR	NR	< 0.001*	Duong, V. et al. (2011)
		2-4 mo.	72/128 (56.2)				
		4-6 mo.	48/55 (87.3)				
		> 6 mo.	118/124 (95.2)				
Unspecified; Both	Nepal	NR	Total: NR/454	NR	NR	≥ 0.15§	Thakur, K.K. et al. (2012)

NR; NR	Laos	Wet: 4-6 mo.	NR/69	69.6 (58.4-80.7)	-	Wet season: 0.02*	Conlan, J.V. et al. (2012)
		Wet: 7-12 mo.	NR/173	85.0 (79.6-90.3)	-		
		Wet: >12 mo.	NR/23	87.0 (72.1-100.0)	-		
		Dry: 4-6 mo.	NR/28	78.6 (62.4-94.8)	-	Dry season: 0.64*	
		Dry: 7-12 mo.	NR/169	71.6 (64.7-78.5)	-		
		Dry: >12 mo.	NR/193	69.9 (71.4-83.0)	-		
Duroc, Landrace, Yorkshire, and hybrids; Female	Vietnam	<1.5 y	NR/57	-	REF	0.002‡	Lindahl, J. et al. (2012)
		1.5-3.5 y	NR/180	-	2.4 (1.2-4.8)		
		>3.5 y	NR/41	-	6.4 (2.2-18.3)		
Unspecified; Both	Malaysia	Young	NR/40 (60.0)	-	1.9 (1.3-2.7)	0.001*	Kumar, K. et al. (2018)
		Adult	NR/50 (25.0)	-	0.4 (0.2-0.7)		
NR; Both	Vietnam	5-8 w	Total: 1,469/2,000 (73.5)	71.7 (68.7-74.7)	-	Significant t‡	Lee, H.S. et al. (2019)
		9-12 w		70.3 (66.8-73.6)	-		
		Mature sow		82.3 (78.1-85.9)	-		
NR; NR	India	<3 mo.	NR/131 (0.0)	-	0 (0.0-0.0)	0.76‡	Kumar, H.B.C. et al. (2020a)
		3 to <6 mo.	NR/199 (5.5)	-	0.6 (0.1-3.3)		
		6 to <12 mo.	NR/316 (10.8)	-	0.9 (0.2-4.8)		
		≥12 mo.	NR/20 (10.0)	-	REF		
NR; NR	Cambodia	2-4 mo.	9/58 (15.5)	NR	NR	< 0.001§	Ladreyt, H. et al. (2020)
		>4-5 mo.	12/28 (42.9)				
		>5-6 mo.	14/26 (53.8)				
Unspecified; Both	Cambodia	3 to >12 mo. (continuous)	Total: 183/197 (92.9)	-	1.7 (1.0-2.8)	0.04‡	Henriksson, E. et al. (2021)
Feral							
Both	Japan	Juvenile		80.0 (NR)	-	> 0.05	

Adult	Total: 30/36 (83.3)	90.9 (NR)	-	Ohno, Y. et al. (2009)
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CI = Confidence interval; NA = Not applicable; NR = Not reported by authors; REF = Referent category.

*Sex and Age are reported for populations where breed was evaluated as a risk factor. Breed and age are reported for populations where sex was evaluated as a risk factor. Breed and sex are reported for populations where age was evaluated as a risk factor. The population information reported for feral pigs is age.

§Results from an univariable mixed effects logistic regression model.

‡Results from a multivariable mixed effects logistic regression model.

*Results from a Chi-squared or Fisher's exact test.

[⊥]Authors reported in text that no significant differences in JEV positivity between males and females was observed; no *P*-value cut-off was stated.

‡Authors reported that seroprevalence in sows was significantly higher compared to animals of other age groups. The difference was deemed statistically significant if the 95% confidence intervals did not overlap.

Table 2.6. Results from observational studies examining associations between farm location and management and Japanese encephalitis virus (JEV) seropositivity in domestic swine, including the number of reports that evaluated each risk factor, risk factor levels, population description, sample size, model-adjusted seroprevalence or odds ratio for JEV positivity, statistical significance of differences, and respective references.

Population [breed; sex; age]	Location	Risk factor level	Positive/ Total (%)	Seroprevalence, % (95% CI) [‡]	Odds ratio (95% CI)	P-value	Reference(s)
Farm location							
<i>Elevation (n = 1)</i>	<i>Summary: Risk of increased JEV seroprevalence as farm location elevation decreased.</i>						
Local, Exotic, and Mixed; NR; Finisher to mature	Nepal	Elevation (1,000 meters)	76/454 (16.7)	-	0.4 (0.2-0.8) [‡]	< 0.01 [‡]	Thakur, K.K. et al. (2012)
<i>Locality (n = 2)</i>	<i>Summary: One of two studies found a risk of increased JEV seroprevalence associated with a farm located in an urban area versus a rural area.</i>						
Local, Exotic, and Mixed; NR; Finisher to mature	Nepal	Urban	53/138 (38.4)	-	4.0 (1.9-8.1) [‡]	< 0.001 [‡]	Thakur, K.K. et al. (2012)
		Rural	23/316 (7.3)	-	REF		
Local and Import; NR; Young to mature	Malaysia	Urban	NR/88 (100.0)	-	0.9 (0.9-1.0)	> 0.05 [*]	Kumar, K. et al. (2018)
		Rural	NR/2 (0.0)	-	REF		
<i>Proximity to rice paddy (n = 1)</i>	<i>Summary: No significant association between a farm located within 200 meters of a rice paddy and swine JEV seroprevalence, after controlling for other factors.</i>						
Local, Exotic, and Mixed; NR; Finisher to mature	Nepal	No	40/323 (12.4)	-	REF	< 0.001 [§] but > 0.05 [‡]	Thakur, K.K. et al. (2012)
		Yes	36/131 (27.5)	-	3.3 (1.9-5.4) [§]		
<i>Proximity to stagnant water (n = 2)</i>	<i>Summary: No significant association between stagnant water within 200 meters of the farm location and swine JEV seroprevalence.</i>						
Local, Exotic, and Mixed; NR; Finisher to mature	Nepal	No	21/194 (10.8)	-	REF	< 0.001 [§] but > 0.05 [‡]	Thakur, K.K. et al. (2012)
		Yes	55/260 (21.2)	-	3.1 (1.8-5.4) [§]		
Local and Import; NR; Young to mature	Malaysia	No	NR/1 (0.0)	-	REF	> 0.05 [*]	Kumar, K. et al. (2018)
		Yes	NR/89 (100.0)	-	0.98 (0.93-1.03)		
Farm management, resources, and infrastructure							

<i>Farm water source (n = 1)</i>		<i>Summary: Significant association between water source and swine JEV seroprevalence.</i>					
Local, Exotic, and Mixed; NR; Finisher to mature	Nepal	Tap	36/279 (12.9)	-	REF	< 0.05 [‡]	Thakur, K.K. et al. (2012)
		Well	19/29 (65.5)	-	7.3 (2.7-19.5) [‡]		
		Common tap	12/32 (37.5)	-	2.3 (0.9-5.9) [‡]		
		River	9/114 (7.9)	-	0.9 (0.3-2.4) [‡]		
<i>Animal source (n = 2)</i>		<i>Summary: No significant association between animal source and swine JEV seroprevalence.</i>					
Local, Exotic, and Mixed; NR; Finisher to mature	Nepal	Same farm	10/29 (34.5)	-	REF	≤ 0.15 ^{\$} but > 0.05 [‡]	Thakur, K.K. et al. (2012)
		Same village	55/224 (24.6)	-	0.6 (0.2-1.4) ^{\$}		
		Same district	11/168 (6.6)	-	0.1 (0.5-0.3) ^{\$}		
		Endemic district	0/33 (0.0)	-	NA		
Local and Import; NR; Young to mature	Malaysia	Same area	NR/45 (46.7)	-	1.1 (0.7-1.6)	> 0.05 [*]	Kumar, K. et al. (2018)
		Same state	NR/45 (42.2)	-	0.9 (0.6-1.4)		
<i>Toilet (n = 1)</i>		<i>Summary: No significant association between restroom availability and swine JEV seroprevalence, after controlling for other factors.</i>					
Local, Exotic, and Mixed; NR; Finisher to mature	Nepal	Restroom	42/366 (11.5)	-	REF	< 0.001 ^{\$} but > 0.05 [‡]	Thakur, K.K. et al. (2012)
		Open	34/88 (38.6)	-	4.9 (2.8-8.3) ^{\$}		
<i>Housing type (n = 3)</i>		<i>Summary: Three of four studies found no significant association between swine housing type and JEV seroprevalence.</i>					
Local, Exotic, and Mixed; NR; Finisher to mature	Nepal	Open		NR	NR	≥ 0.15 ^{\$}	Thakur, K.K. et al. (2012)
		Mixed	Total:	NR	NR		
		Separate enclosed	NR/454	NR	NR		
NR; NR; Finisher to mature	Laos	Penned	Wet: NR/257	81.7 (77.0-86.5)	-	Wet season: 0.16 [*] ; Dry season: 0.001 [*]	Conlan, J.V. et al. (2012)
			Dry: NR/206	77.2 (71.4-83.0)			
		Free range	Wet: NR/4	50.0 (0.0-100.0)	-		
			Dry: NR/167	60.5 (53.0-68.0)			
		Mixed	Wet: NR/0	NA	-		

NR; NR; Weaner to finisher	Cambodia		Dry: NR/6	100.0 (NA)	-	0.3*	Ladreyt, H. et al. (2020)
		Farms	Total: 35/112 (31.3)	26.0 (14.0-40.0)			
		Backyard		35.0 (24.0-48.0)			

Host and vector presence around farm

Presence of mosquitoes (n = 2)

Summary: One of two studies found a risk of increased swine JEV seroprevalence with the presence of mosquitoes at the site.

Local, Exotic, and Mixed; NR; Finisher to mature	Nepal	Yes	73/348 (21.0)	-	3.6 (1.1-2.6) [‡]	0.04 [‡]	Thakur, K.K. et al. (2012)
		No	3/106 (2.8)	-	REF		
Local and Import; NR; Young to mature	Malaysia	Yes	NR/88 (43.2)	-	1.0 (0.9-1.0)	> 0.05*	Kumar, K. et al. (2018)
		No	NR/2 (100.0)	-	REF		

Presence of ardeid birds (n = 1)

Summary: No significant association between the presence of ardeid birds on the farm and swine JEV seroprevalence.

Local and Import; NR; Young to mature	Malaysia	Yes	NR/88 (45.5)	-	1.0 (1.0-1.1)	> 0.05*	Kumar, K. et al. (2018)
		No	NR/2 (0.0)	-	REF		

CI = Confidence interval; NA = Not applicable; NR = Not reported by authors; REF = Referent category.

[§] Results from an univariable mixed effects logistic regression model.

[‡] Results from a multivariable mixed effects logistic regression model.

*Obtained from a Chi-squared or Fisher's exact test.

Table 2.7. Vaccine information, including strain and manufacturer, study design and challenge strain, population and sample size of vaccinated swine, evidence used to determine efficacy, and record information of efficacious vaccine studies for domestic swine organized by vaccine type (live attenuated, killed, multiple type comparisons, and other) and year of publication within vaccine type. Superscripts denote study specific information within the applicable row.

Vaccine information	Study design and challenge strain (Genotype)	Population [breed; sex; age] (sample size vaccinated)	Efficacy evidence	Reference(s)
Live attenuated				
S' strain alone* and a mixture of S' strain and E-strain of the GP series of the hog cholera virus ^a	V&C with Sagara	Other (research); NR; Nursing (n = 3)	Antibody titers; Clinical signs; Viremia	Sazawa, H. et al. (1969b) ^a ; Sazawa, H. et al. (1969a) ^b
S' strain ^{*,a,b}		NR; NR; Weaning (n = 2) Other (research); NR; Nursing (n = 1 ^a ; n = 6 ^b) NR; NR; Weaning (n = 2 ^a ; n = 11 ^b)		
Strain TWN-21*	V&NE	NR; Female; Mature (n = 12)	Antibody titers; Viremia	Lee, G.C.-Y., Huang, Y.-T., and Chang, L.-C. (1975)
Attenuated S-strain*	V&C with AS-6	Landrace; Female; Mature (n = 2)	Antibody titers; Clinical signs; Vertical transmission; Viremia	Fujisaki, Y. et al. (1975)
	VB&C with AS-6	Landrace; NR; Finisher (n = 2)	Antibody titers; Viremia	
Commercially available lyophilized vaccine produced in monkey kidney cell culture [†]	V&NE	Yorkshire/Landrace; NR; Finisher (n = 5)	Antibody titers; Viremia; Virus isolation	Ueba, N. et al. (1978)
Strain M-PK/L [‡]	V&C with JaGAR-01 (GIII)	NR; NR; Weaning (n = NR)	Antibody titers; Transmission to mosquitoes; Viremia	Sasaki, O. et al. (1982)
Killed				
Formalin inactivated JE vaccine for animal use	VB&NE	NR; NR; Grower to mature (n = 2 ^c ; n = 3 ^d)	Antibody titers ^{c,d} ; Viremia ^d	

Formalin inactivated JE vaccine for animal use plus Freund's complete adjuvant [§]		NR; NR; Grower to mature (n = 3 ^{c,d})		Ogata, M. et al. (1969) ^c ; Ogata, M. et al. (1970) ^d
Multiple type comparisons				
Live attenuated m mutant strain*	V&C with Furumoto	Other (research); NR; Nursing (n = 4)	Antibody titers; Clinical signs; Viremia	Kodama, K., Sasaki, N., and Inoue, Y.K. (1968)
Live attenuated ML-17 strain (adapted from JaOH 0566 strain by authors)	V&C with JaGAR-01	NR; NR; NR (n = 2)	Antibody titers; Viremia	Yoshida, I. et al. (1981)
	VB&C with JaGAR-01	NR; NR; NR (n = 2)		
Inactivated JEV vaccine	VB&C JEV SA-14 (GIII)	Yorkshire; NR; Weaning (n = 5)	Antibody titers; Mortality	Li, P. et al. (2008)
Chimeric classical swine fever-Japanese encephalitis viral replicon from a cDNA clone of pA187delE2/JEV-tE*	V&C Beijing P3 (GIII)	NR; NR; Weaning (n = 3)	Antibody titers; Clinical signs; Viremia	Yang, Z. et al. (2012)
Other				
Highly attenuated vaccinia (NYVAC) vectored recombinants (vP908 and vP923)	VB&C with JEV B-2358/84	Landrace; Male; Growing (n = 5)	Viremia	Konishi, E. et al. (1992)
JE-DNA vaccine based on pNGVL4a and a partial dose of a commercial formalin-inactivated vaccine for human use [£]	VB&C with Sw/Mie/40/2004 (GI-b)	Other (research); Female; Mature (n = 2)	Antibody titers; Fetal death	Imoto, J.-I. et al. (2010) [¥]
GI JEV virus-like particles	VB&C with YL2009-4 (GI) and CH1392 (GIII)	Other (research); NR; Weaning to growing (n = 9)	Antibody titers; Clinical signs; Tissue tropism; Viremia	Fan, Y.-C. et al. (2018)
Passive immunization with monoclonal antibodies (JEV-31 mAb or JEV-169 mAb)	Passive immunization & challenge with JE-91 (GI)	Other (research); NR; Weaning (n = 10)	Antibody titers; Clinical signs; Tissue tropism; Viral shedding; Viremia	Young, C.L. et al. (2020)

NR = Not reported; V&C = Vaccinate and challenge; V&NE = Vaccinate and natural exposure; VB&C = Vaccinate, booster, and challenge; VB&NE = Vaccinate, booster, and natural exposure.

* Author produced vaccine.

† Lot L-4 from Kanonji Institute, The Research Foundation for Microbial Diseases of Osaka University, Kanonji, Kagawa.

‡ Biken Laboratories, Japan.

[§]Difco Lab.

[£]JEVAX; Takeda Pharmaceutical Osaka, Japan.

[¥]Report also includes studies comparing inoculation route of the vaccine (needle-free injection vs. normal syringe with needle) and other positive controls.

Table 2.8. Description of Japanese encephalitis virus (JEV) infectious disease models (compartments evaluated in pigs are highlighted in bold), control strategies evaluated, location and reported basic reproduction number

Compartments [‡] (population)	Basic reproductive number [route of transmission [†]]	Control strategy evaluated (if applicable)	Outcomes from control strategies	Location	Reference(s)
SIR (humans); I (pigs); SI (mosquitoes)	-1.00 – 0.50 [vector-borne]	Evaluated control strategies (electronic devices, insecticide treated bed nets, mosquito repulsive lotions, pig vaccination, human treatment, vaccination, and insecticides).	Adopting the three optimal control interventions is the best control strategy to minimize the number of infective pigs and to reduce disease transmission rate.	India	Goswami, N.K. (2022)
SIR (humans); SI (pigs); SI (mosquitoes)	2.01 [vector-borne]	Evaluated optimal control strategies (human vaccination, human treatment, pig vaccination, insecticide application) and their costs.	Combining all control strategies provided optimal disease control and cost.	Indonesia	Kharismawati, H., Fatmawati, and Windarto (2019)
SVIR (humans); SI (pigs); SI (mosquitoes)	0.02 – 2.90 [vector-borne]	Evaluated impact of vaccination and mosquito reduction strategies on controlling disease.	Presented how R_0 varies based on mortality rate of mosquitoes, humans, and pigs.	India	Baniya, V., and Keval, R. (2020)
SEIR (pigs)	1.20 [vector-borne]	Evaluated different vaccination programs (vaccination of 25%, 50%, or 75% of pigs) assuming that efficacy is 95% and that 5% of pigs' infections result from external introductions.	They found there would be a 61%, 82%, and 89% reduction in annual incidence in pigs when 25%, 50%, or 75% of the pigs are vaccinated, respectively. Other assumptions were evaluated in sensitivity analysis.	Bangladesh	Khan, S.U. et al. (2014)
SEICR (pigs); spill-over ratio from reservoirs to humans	0.0013 (95% CI: 0.00 – 0.31) [pig-to-pig]	Assessed the mechanism underlying the JEV skip-and-resurgence patterns between December 2003 and May 2017.	Pig-to-pig transmission increases the size of JEV epidemics, but it is unlikely to maintain the same level of transmission among pigs compared to	Hong-Kong	Zhao, S. et al. (2018)

			vector-borne transmission.		
MSIR (pigs); SEI (mosquitoes)	2.27 – 2.90 [overall] 2.00 – 2.48 [vector-borne] 0.35 – 0.83 [pig-to-pig]	Evaluated the contribution of direct transmission between pigs to the epidemiological cycle of JE.	The contribution of the pig-to-pig transmission on the overall R_0 is 7.5 to 11.9%.	Cambodia	Diallo, A.O. et al. (2018)
MSEIR (pigs, sows, ducks, chickens, cattle, humans, dogs); IES (mosquitoes)	1.07 (95% CI: 0.99 – 1.20) [District 1] 1.25 (95% CI: 1.16 – 1.37) [District 2] 1.38 (95% CI: 1.29 – 1.53) [District 3] Districts in an average village of Kandal province.	Evaluated the influence of host community composition on R_0 for a multi-host system (7 hosts and <i>Culex</i> vectors [vector-borne transmission only]): relative share of competent vs non-competent host body surface area (BSA); relative share of pigs, chickens and ducks among competent hosts BSA; and relative share of cattle among cattle-and-pigs BSA.	When there was a 15% of competent hosts reaching the whole system's BSA R_0 became > 1 ; as the proportion of pigs BSA increased, so did the R_0 , regardless of the percent of chickens; as the percentage of cattle increased, R_0 decreased and when reaching a 65% of cattle among total cattle and pigs BSA, R_0 became < 1 .	Cambodia	Ladreyt, H., Chevalier, V., and Durand, B. (2022)

‡ C = Convalescent; E = Exposed; I = Infected/infectious; M = Maternal antibodies; R = Recovered; S = Susceptible; V = Vaccinated.

† Route of transmission described for pigs only.

95% CI = 95% Confidence Interval.

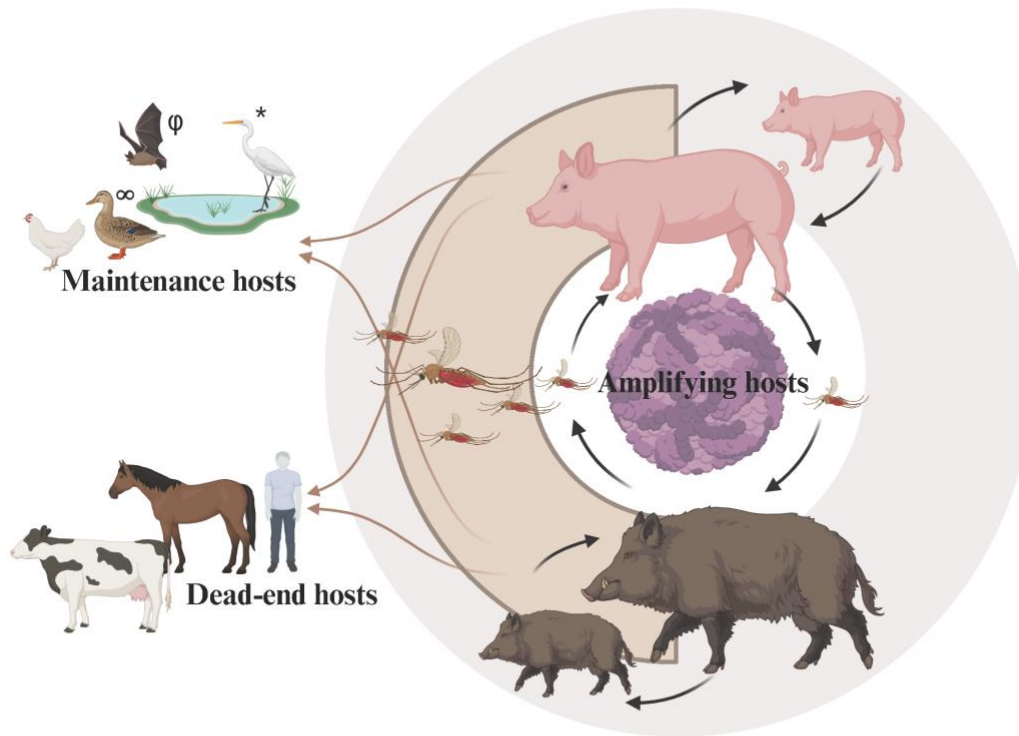


Figure 2.1. Schematic model highlighting the role of domestic and feral swine as amplifying hosts in the transmission cycle of Japanese encephalitis virus.

Created using BioRender.

* Ardeid wading birds (e.g., egret) are maintenance hosts; but may have potential role as amplification hosts

φ Bats may have potential role as maintenance or amplifying host

∞ Other birds (e.g., ducks and chickens) may play a role as maintenance hosts

Host classifications from: Bhattacharya, S. and Basu, P. (2014). Japanese Encephalitis Virus (JEV) infection in different vertebrates and its epidemiological significance: a Review.

International Journal of Fauna and Biological Studies, 1(6), 32-37

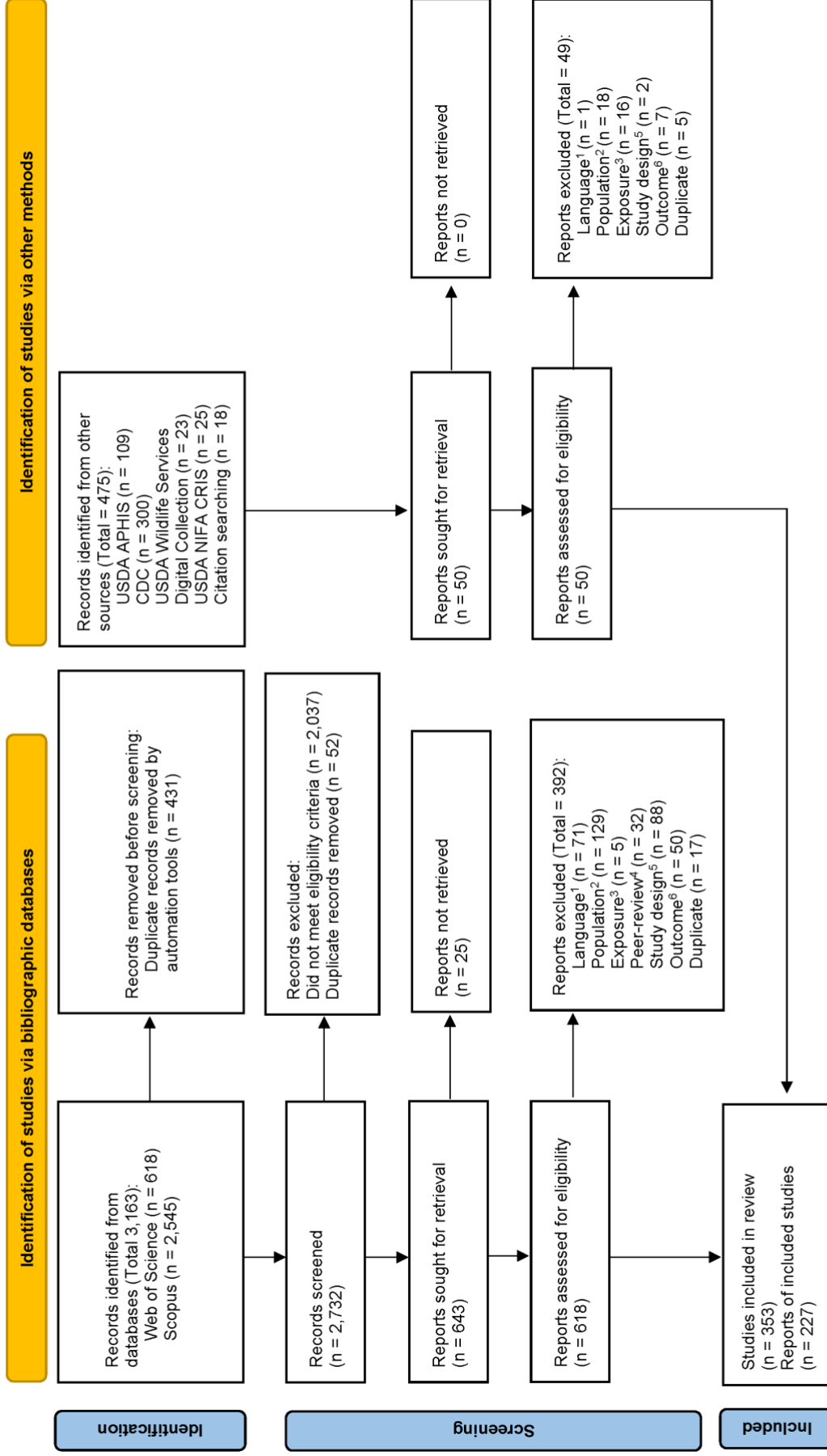


Figure 2.2. Description of Japanese encephalitis virus (JEV) infectious disease models (compartments evaluated in pigs are highlighted in bold), control strategies evaluated, location and reported basic reproduction number.

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 2021;372:n71. doi: 10.1136/bmj.n71. For more information, visit: <http://www.prisma-statement.org/>

¹ Language: Report was not published in English

² Population: Report did not describe outcomes of interest in swine

³ Exposure: Report did not describe JEV-related outcomes

⁴ Peer-review: Report was not published in a peer-reviewed publication

⁵ Study design: Report did not describe original research or a systematic review

⁶ Outcome: Report did not include data on an outcome of interest

Chapter 3 - Understanding metaphylaxis practices for cattle at uncertain risk for bovine respiratory disease across U.S. feedlots: a survey of veterinarians and feedlot managers

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(Submitted to *Translational Animal Science* for publication)

Abstract

Bovine respiratory disease (BRD) is the most frequent and costly disease in United States feedlots. Metaphylactic antimicrobial use effectively reduces morbidity and mortality in cattle at high risk of BRD, however, its implementation is challenging when risk classification is unclear, and the cost-benefit is uncertain. This study aimed to collect and analyze input from feedlot managers and veterinarians on the qualitative and quantitative criteria used to administer metaphylaxis on cattle of uncertain, or “medium” BRD risk. Responses from 25 veterinarians consulting for 617 feedlots (80 to 120,000 animal capacity) across 32 states, and 30 managers overseeing feedlots across 12 states (500 to 120,000 animal capacity) were analyzed. Nearly half of veterinarians (48%) expected BRD morbidity of 15 to 20% and mortality of 2 to 3% in cattle at medium-risk, whereas only about 15% of managers shared these same expectations. Manager

expectations varied widely, with 55% anticipating morbidity of 5 to 15% and no clear consensus on expected mortality. Veterinarians most frequently identified cattle history (64%), weight (59%), commingling (50%), transportation time (50%), and weather (50%) as the primary criteria for determining the need for metaphylaxis in cattle at medium BRD risk. Managers cited similar factors but most often reported source (45%) and origin (35%) as key considerations, with less frequent mentions of weather (14%) and weight (28%). Before cattle arrived at the feedlot, “market channel” was the most influential factor for considering metaphylaxis use according to both veterinarians (73%) and managers (82%), whereas after cattle arrival, “overall cattle health condition” was the most cited factor (69% of veterinarians and 75% of managers). By contrasting the perspectives of veterinary consultants and feedlot managers, we identified consistencies and discrepancies in their perceptions, information use, and the challenges associated with metaphylaxis decisions for these cattle cohorts. These findings contribute to a better understanding of the information that feedlot professionals use and need to guide metaphylaxis decisions in cattle at uncertain BRD risk, thereby supporting efforts toward antimicrobial stewardship and sustainable beef production.

Key words: Bovine respiratory disease, Feedlot cattle, Metaphylaxis, Medium risk, Sustainability

Introduction

Bovine respiratory disease (BRD) has been the most economically important disease and the leading cause of morbidity and mortality in United States (U.S.) feedlot cattle for over half a century (Thomson, 1980; Kelly and Janzen, 1986; Griffin, 1997; Griffin, 1998; Smith, 1998;

Miles, 2009; Johnson and Pendell, 2017). Among feedlots with $\geq 1,000$ animal capacity, evaluated during the National Animal Health Monitoring System Feedlot study in 2011, 16.2% of cattle were affected by respiratory disease (USDA-APHIS-VS, 2013a). This disease accounts for approximately 75% of feedlot morbidities and 50 to 70% of all feedlot mortalities (Edwards, 1996; Galyean et al., 1999; Loneragan et al., 2001; Speer et al., 2001). Economic impacts include costs associated with prevention and treatment, mortalities, decreased feedlot performance, and reduced carcass quality (Griffin, 1997; Smith, 1998). Although precise estimates are challenging due to the wide range of economic factors involved, BRD-related losses have been estimated at \$800 to 900 million USD annually. This figure accounts for reduced feed efficiency, treatment costs, and death loss (Chirase and Greene, 2001).

Management strategies for BRD are typically implemented at the cohort (lot or pen) level, particularly upon feedlot arrival. Many pharmaceutical and biological products have been developed to mitigate BRD, with mixed effectiveness in reducing morbidity and mortality (Edwards, 2010; O'Connor et al., 2013; Stegner et al., 2013; Rogers et al., 2016; Abell et al., 2017; Hanratty et al., 2023). Among these interventions, administration of antimicrobials is one of the most commonly used and impactful (Lofgreen, 1983; Van Donkersgoed, 1992; Terrell et al., 2011). The use of antimicrobials falls into two general categories: 1) “treatment” of clinically ill animals, or 2) “metaphylaxis”, or administration of antimicrobial to a group of high-risk animals to control disease. Antimicrobials labeled for BRD control have been estimated to reduce the risk of BRD morbidity by approximately 1.5-fold compared to a placebo (Tennant et al., 2014; O'Connor et al., 2019). In the absence of BRD metaphylaxis, cattle consistently experience poorer health outcomes and performance metrics, including increased morbidity and mortality, and reduced feed efficiency (Cernicchiaro et al., 2013; Tennant et al., 2014).

Implementation of BRD metaphylaxis on arrival was estimated to generate an annual net return of at least \$532 million dollars to the U.S. beef industry (Dennis et al., 2018). However, in the face of growing concerns about antimicrobial resistance, strategies to reduce antimicrobial usage are being actively explored. A blanket ban on antimicrobial use in food animals is not viable, as it would negatively impact animal health and welfare, food safety, and the economic sustainability of livestock production (Wilson et al., 2017; Dennis et al., 2018). Hence, the judicious use of antimicrobials in animal agriculture, particularly those critical for human medicine, is essential to preserve therapeutic availability and efficacy while safeguarding animal health and welfare, food safety and public health, and the environmental sustainability (AVMA, 2025).

Disease management strategies such as metaphylaxis are effective and approved to use in cattle populations at high-risk for BRD. However, lack of homogeneity in cattle populations and objective decision-making tools to determine metaphylaxis need in cattle make it difficult to consistently identify cohorts at high-risk for BRD. While metaphylaxis decisions are ideally informed by expected disease incidence, in practice, these decisions are often based on subjective assessments due to insufficient or unreliable data (Lechtenberg et al., 1998; Edwards, 2010; Nickell and White, 2010). Upon feedlot arrival, cattle are frequently categorized into BRD “risk groups” using visual appraisal, historical experience with the cattle source (or origin), and other subjective indicators related to behavior and attitude, despite significant heterogeneity within and between groups (Nickell and White, 2010; Taylor et al., 2010a). A national feedlot survey highlighted the lack of pre-arrival information as a barrier to accurate health risk assessment and management (USDA-APHIS, 2000; USDA-APHIS-VS, 2013b).

When pre-feedlot arrival data are available, feedlot health protocols can be adapted to account for prior management, stress associated with transportation, and other environmental exposures (e.g., weather, dust, commingling). For example, transportation distance (or duration) is known to influence BRD morbidity and performance outcomes, but its impact is modified by factors such as region of origin, sex, arrival body weight, and season (Cernicchiaro et al., 2012a; Babcock et al., 2013ab). Similarly, shrink during transport has been associated with BRD health outcomes, carcass characteristics, and gain, but effects vary depending on sex, season, and mean arrival body weight (Cernicchiaro et al., 2012b). Weather conditions also interact with variables such as month of feedlot arrival and cohort size to influence BRD risk (Cernicchiaro et al., 2012b; Wisnieski et al., 2021). The complexity and interdependence of these factors underscore the need for continued investigation into the epidemiology of BRD to support more precise and comprehensive risk classification methods that can inform health interventions in cattle at feedlot arrival.

Due to the subjective nature of BRD risk categorization, disease misclassification is common. When cattle misclassified as low risk later exhibit high morbidity, it poses serious health, welfare, and economic concerns. Conversely, administering metaphylaxis to cohorts with morbidities lower than expected, as reported by Nickell et al. (2021) and Horton et al. (2023), results in unnecessary antimicrobial use. Improving BRD risk classification is critical to minimize inappropriate antimicrobial use, avoid unnecessary treatment costs, and more effectively target populations that require preventive intervention. A survey of feedlot nutritionists estimated that 83% of clients use on-arrival metaphylaxis for high-risk cattle, whereas 39% use it for cattle classified as medium-risk, highlighting a lack of consensus in the management of this intermediate-risk group (Samuelson et al., 2016).

The hypothesis proposed here is that the greatest opportunity to improve metaphylaxis use lies within the subset of feeder cattle deemed to be at medium risk for BRD, a group for which the need and value of metaphylaxis is most uncertain. This study was conducted in alignment with priorities identified by the Foundation for Food and Agriculture Research and the International Consortium for Antimicrobial Stewardship in Agriculture Steering Committee, reflecting an industry-driven effort to address critical knowledge gaps in BRD risk classification and metaphylaxis use in medium-risk cattle. Currently, there is no objective threshold that clearly distinguishes low- from high-risk cohorts, leaving some cattle in this uncertain, intermediate category where predicting health outcomes is often viewed as extremely challenging. In practice, some medium-risk cohorts receive metaphylaxis while others do not (Samuelson et al., 2016), and the criteria driving these decisions remain unclear. Understanding how and why feedlot professionals define and approach medium-risk status, particularly what information, perceptions, or parameters influence their decision to metaphylactically treat or not treat these cohorts, would provide valuable insight for refining metaphylaxis strategies and improving antimicrobial stewardship. The objective of this study was to collect and analyze input from feedlot managers and veterinarians on the qualitative and quantitative criteria used to administer metaphylaxis on cattle of medium BRD risk. By refining BRD risk classification and corresponding metaphylaxis use, this work aims to support the sustainability of the U.S. beef industry through more judicious antimicrobial use while enhancing animal health and well-being.

Materials and Methods

This survey was developed by the study authors at Kansas State University, and all procedures were approved by the Kansas State University Institutional Review Board (No.

11898 [Veterinarian Survey] – Appendix A; No. 11619 [Feedlot Manager Survey] – Appendix B).

Questionnaire development and survey implementation

An online questionnaire was developed to characterize U.S. feedlot veterinarians' and managers' perceptions, information sources, and decision-making criteria used when considering metaphylaxis use for cattle at medium risk for BRD. The questionnaire used for the survey was created by investigators at Kansas State University in partnership with a seven-member steering committee of feedlot professionals who possess extensive expertise in beef cattle production, business management, and industry trends. Their guidance ensured that the questionnaire used for the survey reflected current industry practice realities and knowledge gaps of priority.

Structured discussions with the steering committee identified critical knowledge gaps in metaphylaxis decision-making for cattle cohorts assessed as having medium BRD risk. These gaps helped inform the formulation of specific survey questions. Investigators drafted the initial questionnaire, after which every question underwent iterative revisions to verify clarity, relevance, and alignment with the objectives. Revisions focused on eliminating ambiguity, minimizing participant burden, and preserving content relevance.

The finalized questionnaire was designed in Qualtrics (Provo, UT) for electronic dissemination. Two audience-specific versions, one for veterinarians and one for feedlot managers, were created with parallel content but audience-appropriate wording. The final version of the questionnaires consisted of 32 questions for the veterinarians and 26 questions for the managers in various formats, including fill-in-the-blank or short-essay questions, multiple-choice, and ranking- and rating-type (i.e., Likert-scale) questions. Questions were grouped into six subject-based sections: (1) Demographics (Part 1), which consisted of a conditional eligibility

question asked only in the veterinarian's survey ("How many feedlots, including both finishing and starter/grow yards, do you provide services for?"), for which answers equal to "0" would prompt the participant to the end of the survey; (2) Moderate or Medium Risk Classification for BRD, with questions related to the classification and management of cattle at medium BRD risk; (3) BRD Management, characterizing general strategies and protocols used for BRD prevention in all risk categories; (4) Feedlot Population Demographics, covering feedlot size, resources, and cattle turnover; (5) Cattle Population Demographics, collecting data on cattle characteristics, such as age, sex, breed-purpose, and origin; and (6) Demographics (Part 2), which captured additional information such as states of practice, years of experience, and number of feedlots consulted, or managed, during the time of survey participation.

After consensus was reached on format and wording of the questions among investigators at Kansas State University, pre-testing was conducted with steering-committee members representative of the target population (i.e., the veterinarian survey questionnaire was pre-tested by individuals of the steering committee, and the feedlot managers survey questionnaire was pre-tested by employees within steering committee members' organization). Their feedback on comprehension, terminology, and flow of questions informed further refinements. The revised versions were then pilot-tested with additional veterinarians and feedlot personnel recruited through the steering-committee members' network. Pilot testing evaluated practicality, estimated completion time, and logic of questions; resulting suggestions prompted minor adjustments to enhance participation and data quality before broader dissemination of the questionnaires.

Data collection occurred from February to April 2024 for veterinarians and from September 2024 to February 2025 for feedlot managers. During these periods, the online questionnaires remained open for participation. For partially completed responses, automatic

submission was triggered 30 days after the survey questionnaire link was opened, capturing responses as-is if participants did not formally submit the questionnaire within that timeframe.

Study population and recruitment

There were two targeted respondent groups: (1) veterinarians who consulted for U.S. feedlots in 2023 on the use of metaphylaxis in cattle at medium risk of developing BRD, and (2) feedlot managers actively managing feedlot operations during the time of survey participation. Veterinarians received an invitation to participate in an online survey questionnaire through the following electronic mailing lists: American Association of Bovine Practitioners (AABP; approximately 5,000 recipients), Academy of Veterinary Consultants (AVC; approximately 900 recipients), and via the networks of the principal investigators and steering committee members, which disseminated the questionnaire to their corresponding organization members and affiliates. Feedlot managers received a similar invitation to participate in a different online questionnaire through: Feed-Lot Magazine (approximately 5,720 recipients), AgManager.info (8,524 recipients), K-State Animal Science Focus on Feedlots (396 recipients), and e-mail contacts within the steering committee and authors' network. In addition, AABP and AVC members were recruited to help disseminate the feedlot managers survey questionnaire within their networks. Veterinarians answered questions based on the combined pool of all feedlots they consult for, reflecting their broader perception across multiple operations. Feedlot managers provided responses specific to their operation(s), typically within the same organization when managing more than one. This distinction highlights the difference in the observational unit between the two respondent groups. Reminders were distributed approximately once per month via all initial dissemination channels. Although the mailing lists targeted the surveys' populations of interest, the number of recipients does not necessarily reflect the number eligible to participate.

Both, the veterinarian (Appendix A) and the feedlot manager questionnaires (Appendix B) were open to any individual with the access link. Participation in the survey was voluntary, and participants were allowed to skip any question (except the first question for veterinarians: “How many feedlots, (include both finishing and starter/grow yards), do you provide services for?”) or to stop at any point throughout the study. Participants were informed that their responses were anonymized with all identifiers removed, and results were being published in aggregate form. Respondents were also assured that responses collected during this survey would not be used or distributed for future research studies. Therefore, data were collected from participants through a self-administered online questionnaire, written in English, with an informed anticipated time for completion between 15 and 30 minutes. No incentives were offered for questionnaire completion.

Data analysis

Responses to the veterinarians’ questionnaire were included in the analysis if respondents reported consulting for at least one feedlot in the initial screening question. All submitted responses to the veterinarian and feedlot manager questionnaires were included, regardless of completion status. Data were exported from Qualtrics[®] as a Microsoft Excel file.

Descriptive analyses were performed for each survey question independently. Closed-ended questions (e.g., multiple-choice, ranking, rating, and checklists) were summarized using frequencies and percentages for categorical responses and measures of central tendency and dispersion for continuous responses. For some questions, in addition to selecting predefined risk factors from a checklist, respondents were invited to elaborate through open-text comments. For example, descriptive criteria used to classify cattle at medium risk for developing BRD by veterinarians and feedlot managers was solicited with a question utilizing an open answer format

at the beginning of the questionnaire. The order and format of this question was designed to obtain unprompted responses from participants (i.e., before viewing potential concepts or ideas from the remaining survey questions or developing survey fatigue). Open-text responses were analyzed using qualitative content analysis. Responses were reviewed and categorized into common themes. Data management, analysis, and visualization were conducted using Python (version 3.12) in Jupyter Lab (version 4.2.1), employing packages including ‘pandas’ for data manipulation, ‘matplotlib’ and ‘seaborn’ for plotting, and ‘numpy’ for numeric operations. Microsoft Excel was also used for supplemental data summarization and figure preparation.

Results

Survey participation and population demographics for veterinarians and feedlot managers are presented first and separately for each participating professional group. Findings related to metaphylaxis decision-making in medium-risk cattle, changes in attitudes towards metaphylaxis use over time, and perceived information gaps and management opportunities to optimize BRD metaphylaxis use are then presented by comparing and contrasting responses between participating groups.

Veterinarian questionnaire

A total of 75 online questionnaires, targeted to feedlot veterinarians, were opened and (or) initiated by an anonymous IP address, meaning that an individual received the invitation and opened the questionnaire link. Of those, nine individuals left all questions blank, and one individual responded “zero” for question 1 (i.e., screening question for participants’ eligibility: “How many feedlots, (include both finishing and starter/grow yards), do you provide services for?”), meaning that the participant was ineligible to participate. Among the 65 veterinarians who answered the first question with a number greater than zero (meaning they consulted for at

least one feedlot in 2023), 40 left all remaining questions blank and only 25 answered at least one more question. The responses from the 25 veterinarians who completed (or partially completed) the questionnaire were summarized on a question-basis (i.e., each question may have a different number of respondents). Among the 21 veterinarians who completed and submitted the questionnaire (as opposed to finishing and not clicking submit or abandoning mid-way through completion: 4 out of 25), the median time for completion of the questionnaire was approximately 36 minutes (ranging from a minimum of 17 minutes to a maximum of 2 days).

Veterinarian demographics

Twenty-five veterinarians responded to at least two questions. Participants reported consulting for a minimum of one feedlot and a maximum of 150 feedlots, with a median of 15 feedlots, and a mean of 25 feedlots. In regard to feedlot consulting experience, 57% of participants ($n = 12$ veterinarians) reported having more than 15 years of experience, 19% ($n = 4$) had between 10 and 15 years, and another 19% reported having between 5 and 10 years of experience. Of the 21 respondents, only one reported having fewer than five years of feedlot consulting experience. Collectively, participating veterinarians consulted for a total of 617 U.S. feedlots in 2023, across 32 different states. The most frequently reported state was Kansas (12), followed by Nebraska (7) and Texas (7). Other states mentioned included Colorado, Idaho, Oklahoma, and Iowa (each reported by 5 veterinarians), as well as Washington (3), Wyoming (2), Ohio (2), and Indiana (2). The remaining states, each mentioned by one participant, included Alabama, Arizona, California, Florida, Georgia, Illinois, Kentucky, Louisiana, Michigan, Mississippi, Missouri, Montana, Nevada, New Mexico, New York, Oregon, Pennsylvania, South Carolina, South Dakota, Tennessee, and Virginia. Five out of 25 participants did not respond to this question.

Veterinarians' feedlots and cattle demographics

Descriptive statistics of feedlot and cattle population demographics from veterinarians who participated in the survey are shown in Table 3.1. The smallest feedlot (one-time capacity) that participating veterinarians consulted for in 2023 averaged 2,457 cattle and ranged from 80 to 15,000 cattle. The average capacity of their largest feedlot was 59,429 cattle, ranging from 5,000 to 130,000 cattle. The average total number of cattle across all feedlots that each veterinarian consulted for in 2023 was 452,333, with totals ranging from 10,000 to 2,000,000 cattle. On average, participants reported that 33% of the cattle they consulted for in 2023 were exclusively owned by feedlot customers, 42% were exclusively owned by the feedlot itself, and 9% were under shared ownership between the customer and the feedlot.

Across all feedlots, participants reported that, on average, 50% of the cattle they provided veterinary services for in 2023 were yearlings, 47% were calves, and 3% were classified as “other”, or of unspecified age. Across all feedlots, the cattle population consisted primarily of steers (53%), followed by heifers (34%), bulls (10%), and spayed heifers (2%). The majority (82%) were beef breeds, with the reminder comprising dairy cattle or beef-on-dairy crosses. Most cattle (88%) were reported to be of U.S. origin.

Feedlot manager questionnaire

A total of 120 online survey questionnaires, targeted to feedlot managers, were opened and (or) initiated by an anonymous IP address. Of those, 90 left all questions blank or abandoned the questionnaire without participating. The remaining 30 individuals who opened the questionnaire responded to some or all questions. Among the 23 respondents who completed (or partially completed, 7) the questionnaire, the median time for completion was approximately 25 minutes (ranging from a minimum of 4 minutes and a maximum of 7 days).

Feedlot manager demographics

Fifty two percent of feedlot managers who participated in the questionnaire (15 managers) reported having more than 15 years of experience, 24% (7 managers) reported between 10 and 15 years, and 10% having between 5 and 10 years. Four participating managers (14%) indicated fewer than 5 years of experience. Although the median number of feedlots managed per participant was 1, responses ranged from 1 to 5, averaging 1.5 feedlots per manager. Feedlots were located across 12 different states, with the majority located in Kansas (8) and Texas (7), followed by Colorado (2), and Iowa (2). The remaining states were mentioned once, and included New Mexico, Ohio, Michigan, Minnesota, Kentucky, South Dakota, Idaho, and Oregon. One participant indicated “Several” and two other participants left the answer field blank.

Managers’ feedlot and cattle demographics

Descriptive statistics of feedlot and cattle population demographics from managers who participated in the questionnaire are shown in Table 3.2. Feedlot managers reported an average one-time feedlot capacity of 29,550 cattle, with a median capacity of 24,000 cattle and an interquartile range (IQR) of 2,100 to 50,000 cattle. The average reported number of feedlots’ home pens was 202 (median of 209), most commonly ranging between 15 and 375 pens (IQR). The median for minimum pen size was 50 cattle, ranging most commonly (IQR) from 38 to 71 cattle/pen. The median for maximum pen size was of 300 cattle, with an IQR of 200 to 350 cattle per pen. Regarding cattle ownership, managers reported that, on average, 38% of the cattle were exclusively owned by customers (ranging from 0 to 100%), 46% were exclusively owned by the feedlot (ranging from 0 to 100%), and 7% were jointly owned by the feedlot and customer (ranging from 0 to 25%).

Veterinarians and managers' perspectives on metaphylaxis decisions in medium-risk cattle

Original open-text responses on criteria used to classify cattle as medium risk were categorized according to broader themes and are summarized in Figure 3.1. Both veterinarians and feedlot managers reported cattle history-related factors (i.e., health, weaning, vaccination, and backgrounding [61% and 50%, respectively]), cattle source (57% and 68%, respectively), body weight (59% and 29%, respectively), and transportation time (or distance travelled) (50% and 36%, respectively) among the top five criteria most frequently used to classify cattle at medium risk for BRD. Other criteria frequently described by veterinarians included level of commingling (45%) and weather (50%), whereas feedlot managers more frequently described others such as origin (36%) and age (29%). Notably, when asked how the BRD risk classification varies across feedlots, the majority of veterinarians (65%; 13 out of 20 respondents), indicated that classification criteria often vary to some extent, depending on feedlot-specific characteristics and resources, such as facilities, labor availability and experience, cattle sourcing, feeding practices, weather, ownership, and mortality tolerance. In contrast, 30% (6 out of 20 respondents) reported using very similar or identical risk classification criteria across feedlots.

Expected morbidity and mortality frequencies for cattle considered to be at medium risk of developing BRD differed between veterinarians and feedlot managers and are shown in Figures 3.2 and 3.3 (respectively). The majority of veterinarians expected a morbidity of $> 15\%$ and $\leq 20\%$ (48% of responses) and mortality of $> 2\%$ and $\leq 3\%$ (48% of respondents) in these cattle at medium risk of developing BRD. Only 14% and 17% of feedlot managers shared these same expectations for morbidity and mortality (respectively) as the veterinarians. In general,

feedlot managers' expectations for morbidity and mortality were broader than veterinarians across the proposed ranges, with less overlap in perspectives overall. The expected morbidity was reported to be of $> 10\%$ and $\leq 15\%$ by 31% of the respondents, followed by 24% reporting an expectation of $> 5\%$ and $\leq 10\%$, and another 24% reporting an expectation $> 20\%$ and $\leq 25\%$. Similarly, 28% of managers shared an expected mortality of $> 5\%$, whereas 24% expected mortalities to be $> 1\%$ and $\leq 2\%$, and another 24% expected a mortality of $> 3\%$ and $\leq 4\%$.

Regarding which individuals (i.e., by job role) are typically involved in the decision to use metaphylaxis in medium-risk cohorts, the majority of managers' responses aligned with veterinarians' recommendations, suggesting consistency in the view that both veterinarians and feedlot managers should be involved in the metaphylaxis decision for cattle at medium BRD risk, both before and after cattle arrival. All surveyed veterinarians (100%) recommended feedlot managers be involved in the metaphylaxis decision before cattle arrival, and most (87%) did so for after arrival as well. This was consistent with the managers' responses, with 83% indicating involvement before and 72% after cattle arrival. Veterinarians also commonly recommended themselves (or peers) be involved in the decision-making process (87% before and 83% after arrival), and this was confirmed by 62% of managers for both time points. Involvement of hospital crew leads in the decision-making process was notably recommended by 70% of veterinarians after cattle arrival, although only 38% of managers confirmed this role's involvement. Some veterinarians (17%) and managers (17%) also suggested the hospital crew leads' involvement before cattle arrival. Cattle managers also were frequently recommended or reported to be involved in the metaphylaxis decision after cattle arrival (22% of veterinarians and 66% of managers) and, to a lesser extent, before arrival (13% of veterinarians and 55% of managers). Other roles, such as "cowboy", "owner", "customer", "buyer", "marketing manager",

and “receiver” were cited less frequently. Ultimately, both veterinarians (61%) and managers (64%) most often identified feedlot managers as the individuals responsible for making the final decision about metaphylaxis use for cattle at medium BRD risk.

On average, veterinarians estimated that metaphylaxis decisions are made prior to cattle arrival, based solely on procurement or pre-arrival factors, for an average of 43% of pens (median: 40%, range: 0 to 100%). In contrast, veterinarians estimated that metaphylaxis decisions were driven primarily by purchase price or break-even calculations for only 13% of pens, on average (median: 0%, range: 0 to 75%). Feedlot managers provided similar estimates, reporting that, on average, metaphylaxis decisions were made before cattle arrival based on procurement factors for 47% of pens (median: 40%, range: 0 to 100%), and were primarily influenced by purchase price or break-evens in 8% of pens (median: 0%, range: 0 to 100%).

Although several factors are considered when making metaphylaxis decisions both before and after cattle arrive at the feedlot, survey participants were asked to rate these factors based on their perceived level of impact. Likert-scale results depicting the influence of these factors on veterinarians’ and feedlot managers’ decisions about whether to use or not use metaphylaxis in cattle at medium risk for developing BRD are presented in Figures 3.4 and 3.5, respectively.

Before cattle arrival, the majority of veterinarians reported that market channel (73%), body weight (69%), potential mortality (65%), and region of origin (60%) had an extremely high impact on their decision-making process. Conversely, more than 50% of veterinarians indicated that concerns about antimicrobial resistance in people, the number of home pens, and cattle sex had little to no impact. Factors such as cattle ownership (56%), animal welfare (60%), overall health condition (60%), and season (55%) were most commonly reported to have a medium to high impact on the metaphylaxis decision prior to arrival (Figure 4). The importance assigned to

these factors by feedlot managers showed slight differences compared to veterinarians' responses. Managers most frequently reported that prior experience with the producer (82%), the market channel (72%), backgrounding or pre-conditioning status (69%), and region of origin (58%) had an extremely high impact on their metaphylaxis decisions before cattle arrival (Figure 5). Similar to veterinarians, the majority of managers (> 50%) considered the number of home pens and animals per pen, sex of the cattle, cattle ownership, and concerns about antimicrobial resistance in people to have little to no impact. Weather conditions (50%), pen conditions such as mud (44%), transport distance (41%), animal welfare (40%), and shrink (40%) were most often reported to have a medium to high impact.

After cattle arrival at the feedlot, the most frequently cited factor with extremely high impact on metaphylaxis decisions was overall cattle health, reported by 69% of veterinarians (Figure 3.4) and by 75% of managers (Figure 3.5). Following this, veterinarians most frequently assigned extremely high impact to weather conditions (56%), potential mortality (56%), and region of origin (52%), while managers most frequently emphasized market channel (71%), region of origin (65%), and prior experience with the producer (62%). Across both groups, the number of home pens and animals per pen, concerns about antimicrobial resistance in people, sex of the cattle, and cattle ownership remained among the least impactful factors, even after cattle had arrived at the feedlot.

A subsequent question with an open-text response format was included to allow the feedlot professionals to report any additional subjective (and, if applicable, objective) factors influencing their decisions on whether to use metaphylaxis in cattle at medium BRD risk. Among the subjective factors reported (Figure 3.6), attitude and history were most frequently cited as influential before cattle arrived at the feedlot. After arrival, attitude remained important,

but appearance became a more prominent factor than history in guiding the metaphylaxis decision.

Changes in participants' attitudes towards metaphylaxis use over the past years

In recent years, a combination of factors, including declining U.S. cattle inventory, record-high prices (unadjusted for inflation) for beef cattle and derived products, and relatively low costs of drugs approved for metaphylactic use in high-risk cattle, prompted survey questions about current metaphylactic use compared to five years ago (e.g., between 2018 and 2020). Veterinarians reported that the average percentage of feedlot pens that did not receive metaphylaxis but, in hindsight, should have, remained unchanged in 2023 compared to historical levels, with both periods averaging approximately 20% (Figure 3.7). However, when asked to estimate the percentage of pens that did receive metaphylaxis but, in hindsight, may not have needed it, responses showed an upward shift in the distribution for 2023 relative to historical estimates (Figure 3.7). In contrast, although feedlot managers' median estimates were numerically higher historically compared to 2023, the distribution of responses (i.e., minimum and maximum estimates) remained similar for both time points, in both scenarios, i.e., (1) pens that did not receive metaphylaxis but, in hindsight, should have, and (2) pens that received metaphylaxis but, in hindsight, may not have needed it (Figure 3.8).

Participants were also asked to estimate whether the proportion of pens receiving metaphylaxis in 2023 had changed compared to 3 to 5 years prior; again, survey responses revealed considerable variability in reported use over time (Figure 3.9). Specifically, 41% of feedlot managers and 17% of veterinarians indicated that the proportion of pens receiving metaphylaxis in 2023 was similar to five years ago. In contrast, 42% of managers and 57% of veterinarians reported an increase of more than 10% in metaphylaxis use, implying that for some

operations, BRD risk (or perceived risk) was elevated, or that economic or operational conditions favored more aggressive BRD metaphylaxis. Only 10% of managers and 4% of veterinarians reported that the proportion of pens that received metaphylaxis in 2023 was lower by some amount compared to historical use (i.e., selected the multiple-choice options of “less than 10% lower in 2023”, “10 to 20% lower in 2023”, or “more than 20% lower in 2023”).

Information gaps and management opportunities to optimize BRD metaphylaxis use

Participants’ response frequencies on types of subjective and objective information they wish they had more often or with greater accuracy when deciding whether to use metaphylaxis in cattle at medium risk are depicted in Figure 3.10.

The majority of veterinarians (87%) and feedlot managers (85%) indicated a desire to have vaccination records available more often or with greater accuracy when making metaphylaxis decisions for cattle at medium risk for BRD. Based on the author’s synthesis of veterinarians and managers open-text responses regarding how this factor influences their decision, respondents generally agreed that evidence of prior viral and bacterial immunity, such as recent vaccination with modified-live vaccines, would lower perceived BRD risk and reduce the likelihood of using antimicrobial metaphylaxis. Some participants noted that knowing whether calves had received two doses of modified-live vaccines prior to feedlot entry would suggest better health outcomes and might shift animals out of the metaphylaxis-eligible group. Additionally, several respondents mentioned that access to vaccination records could influence processing protocols, help avoid redundant or unnecessary vaccinations on arrival, and reduce the risk of under- or over-use of antimicrobials. Others mentioned that, in some cases, a history of intranasal or killed vaccines could increase perceived BRD risk, pushing cattle to the high-risk

category. Ultimately, participants viewed access to vaccination records as a tool for making more informed, individualized decision on metaphylaxis use.

Similarly, the majority of veterinarians (83%) and feedlot managers (85%) expressed interest in more consistent and accurate access to weaning records when evaluating the need for metaphylaxis in cattle at medium BRD risk. Across responses, longer weaning periods prior to shipping cattle were consistently associated with lower perceived BRD risk and a lower likelihood of metaphylaxis use by the respondents. Participants frequently cited 45 to 60 days as a critical threshold, emphasizing that calves weaned for fewer than 45 days were generally considered higher risk and more likely to be given metaphylaxis. In contrast, animals weaned for 60 days or longer, were viewed as better adapted and less immunocompromised, leading to a reduced perceived need for metaphylaxis. Several responses also emphasized that bawling calves aid as behavioral indicators of recent weaning and weaning stress, leading to a high-risk categorization when precise information is not available, reinforcing the importance of knowing the weaning timeframe to improve BRD risk classification and metaphylaxis decisions.

In addition to vaccination and weaning history, respondents identified several other types of information they wished were more readily available or accurate when making metaphylaxis decisions. Treatment records were cited by 83% of veterinarians and 77% of managers as valuable for assessing prior health events and informing metaphylaxis use (i.e., what percentage of the cattle has been treated before and how long ago, and what drug(s) have been used would help guide the metaphylaxis decision). A smaller, but still notable, proportion of veterinarians (61%) and managers (46%) indicated that knowing the calves' previous rations could aid in evaluating their nutritional background and potential disease susceptibility (some mentioned that "bunk broke" calves experience less transition stress between the two production phases). Feed

intake records also were mentioned by 44% of veterinarians and 39% of managers as helpful for metaphylaxis decision-making by informing pre-arrival gut health and supporting optimal feeding and nutritional strategies upon feedlot arrival to minimize stress and disease susceptibility (author's interpretation of open-text responses on how this factor aids in their decision). Lastly, while subjective visual assessments, such as whether cattle appeared "fleshy" or "skinny," were more commonly valued by veterinarians (44%), 27% of managers expressed similar interest in having this type of information more often or more accurately.

In an open-text question response, veterinarians were asked what management strategies they believe could reduce metaphylaxis use in cattle at medium risk for BRD. Among the 23 respondents, several key themes emerged, with many emphasizing improvements in cattle sourcing (26%) and pre-arrival management (26%). Commonly mentioned strategies included longer weaning periods, revaccination at least two weeks before shipping, parasite control, backgrounding, and avoiding sale barns in favor of direct-from-ranch procurement. Veterinarians also highlighted the importance of improving information sharing (e.g., vaccination records, ration and days-on-feed history prior to feedlot arrival) and traceability (17%), improving pen conditions, maintaining lower stocking densities with greater bunk and water space upon arrival (17%), minimizing commingling (13%), formulating "milder" receiving rations (9%), and reducing transport stress (i.e., advocating for shorter transit times; 9%). Economic considerations were also noted, such as lower cattle prices (9%), higher drug costs (17%), decreased days-on-feed (4%), and rewarding producers who supply lower-risk cattle where metaphylaxis is unnecessary (4%). Some respondents pointed to the potential influence of regulatory initiatives (4%), while others emphasized the need for additional research to identify situations where metaphylaxis may not be required, supporting more data-driven and "unemotional" risk

classification (13%). Additional suggestions included increasing labor availability with skilled animal handlers (13%), and surveillance-based diagnostics at arrival (4%). One participant raised broader systemic concerns, suggesting that metaphylaxis use reflects other underlying challenges in the cattle production system, including labor constraints and feedlot design, rather than being solely a cattle health issue, and emphasized improving pre-purchase management alignment to better match cattle with feedlot capabilities as a way to reduce metaphylaxis use.

Discussion

Bovine respiratory disease is the leading reason for antimicrobial use in U.S. feedlots (USDA APHIS, 2019), resulting in a considerable burden to animal health, welfare, and productivity. Antimicrobial metaphylaxis is one of the most effective strategies to reduce BRD morbidity and mortality in high-risk populations (Lofgreen, 1983; Guthrie et al., 2004; Ives and Richeson, 2015). Although established BRD risk factors can help classify cattle as clearly high- or low-risk (Sanderson et al., 2008; Taylor et al., 2010a; Cernicchiaro et al., 2012a,b), cattle in the medium-risk category — those with overlapping characteristics of both groups — pose a challenge for accurate risk classification and metaphylaxis decision-making (Wilson et al., 2017; Horton et al., 2023; Szasz, 2024). A survey of feedlot nutritionists estimated that 83% of clients use on-arrival metaphylaxis for high-risk cattle, whereas 39% use it for cattle classified as medium-risk, highlighting the lack of consensus in managing this latter group (Samuelson et al., 2016). Recognizing this gap, the Foundation for Food and Agriculture Research and the International Consortium for Antimicrobial Stewardship in Agriculture working groups identified metaphylaxis decision-making for medium-risk cattle as both a major area of uncertainty and an important opportunity to advance antimicrobial stewardship. In response, this study was conducted as an industry-driven effort to better understand how feedlot veterinarians and

managers approach metaphylaxis decisions in medium-risk cattle. Our findings highlight three key takeaways: (1) the expected BRD morbidity and mortality, and the criteria used to classify cattle at medium risk are often subjective and varied both between and within feedlot professional groups, leading to inconsistent metaphylaxis practices; (2) veterinarians and managers rely on similar types of information but prioritize these factors differently; and (3) although perceptions regarding antimicrobial use versus need varied, most participants from both professional groups agreed that antimicrobial use has increased, by some amount, in recent years compared to historical levels.

This study provides insight into how veterinarians and feedlot managers approach BRD risk classification and metaphylaxis use in medium-risk cattle. While there could be debate over whether a distinct “medium-risk” category should be formally acknowledged in BRD risk classification and management protocols, it is tacitly understood that risk classification is a subjective process. As such, no objective threshold currently exists to clearly distinguish between low- and high-risk cohorts, leaving some cattle in an uncertain, intermediate category. Although limited data exist on the proportion and significance of each BRD risk category within the U.S. cattle feeding industry, Szasz (2024) referenced the adage “80% of your problems come from 20% of the cattle,” to describe these medium-risk cohorts. According to our survey, both veterinarians (across all feedlots they advised in 2023) and feedlot managers (within their own operations) reported that approximately 30% of the cattle under their care fell into the medium-risk category. Moreover, despite representing a significant portion of U.S. cattle on feed, these cohorts remain much less studied, leaving their optimal management approaches uncertain and underexplored.

Questionnaires were tailored to feedlot veterinarians and managers, the two professional groups most directly involved in evaluating BRD risk and making metaphylaxis decisions. Supporting the relevance of the study's target population, most respondents from both groups confirmed that they play a central role in determining whether to administer metaphylaxis in cattle at risk for BRD. Furthermore, our findings suggest that both veterinarians and managers rely on a range of information to classify risk and justify metaphylaxis use, highlighting areas of alignment as well as some inconsistencies in how they assess BRD risk and make management decisions.

When objectively assessing BRD risk in feedlot cattle, prior research has used a 15% expected morbidity threshold within the first 45 days post-arrival to distinguish low- from high-risk cohorts (Rojas et al., 2022). Consistent with this, most veterinarians in the current survey estimated BRD morbidity for medium-risk cattle between 15% and 20%, with expected mortality between 2% and 3%. In contrast, feedlot managers showed broader perspectives, with no clear majority range of expected morbidity and mortality for these cohorts of cattle. Veterinarians' estimates are supported by empirical data from Horton et al. (2023), who reported approximately 17% BRD morbidity and 2.5% mortality in medium-risk cattle that were not given metaphylaxis on arrival. However, Nickell et al. (2021) reported greater variability in morbidity (19% to 35%) and lower mortality (under 1%) in cattle similarly classified, depending on the location (Texas, Oklahoma, or Nebraska). These contrasting expectations likely reflect fundamental differences in the reference frames used by each group. Veterinarians, who often work across multiple operations and regions, may base their estimates on aggregated experiences and population-level data, leading to more consistent and centered estimates. In contrast, feedlot managers tend to rely on firsthand experiences within a single operation, where BRD outcomes may be influenced by

unique management practices, cattle sourcing, or environmental conditions. As a result, their estimates tend to be more operation-specific, which may contribute to the observed wider variability, both between (veterinarians vs managers) and within (among managers) professional groups. This divergence highlights the importance of aligning perceptions of disease risk between veterinarians and managers, as it may influence the timing and appropriateness of metaphylactic interventions.

Once respondents identified which cohorts they considered to fall into this medium-risk category, the remainder of the questions were designed to gather information on the current industry practices for managing BRD in these specific groups of cattle. The lack of consensus in classifying risk and determining the need for metaphylaxis in this population presents an opportunity to improve decision-making. More specifically, it highlights the need for information that supports more precise, evidence-based metaphylaxis decisions. Reducing unnecessary antimicrobial use is central to antimicrobial stewardship, whereas improving animal health and reducing morbidity and mortality can enhance production efficiency and decrease the environmental footprint of beef production (Horton et al., 2023). While goals of minimizing drug use and maximizing productivity, may seem at odds, they ultimately converge in the pursuit of sustainable and responsible cattle production. Thus, reducing uncertainty and improving our understanding of how feedlot professionals currently classify medium-risk cattle and decide on metaphylaxis is a critical step toward aligning stewardship and sustainability goals in practice.

To explore how cattle are classified as medium risk for BRD, the questionnaires began with an open-text response-format question designed to capture participants' most intuitive and unbiased responses before any potential survey fatigue. The majority of both veterinarians and managers reported using cattle history as the primary basis for classifying animals in this

medium risk category. This included references to vaccination and weaning history, preconditioning, backgrounding, and feeding history, collectively grouped under the theme of “cattle history”. These criteria align with prior research recommending preconditioning status as an initial indicator to distinguish calves as either low- or high-risk (Wilson et al., 2017).

Preconditioned calves have consistently demonstrated lower BRD incidence and better health outcomes during the feedlot phase (Roeber et al., 2001; Step et al., 2008; Richeson et al., 2012). In this context, it is unsurprising that 55% of veterinarians suggested improving preconditioning practices, such as backgrounding, extending weaning periods, revaccination at least two weeks prior to shipping, parasite control, and balanced nutrition, as primary strategies to reduce metaphylaxis use in feedlot cattle at medium BRD risk. For cattle not clearly classified as low- or high-risk, Wilson et al. (2017) recommended incorporating additional lot-specific factors to guide decision-making. Accordingly, the majority of both veterinarians and managers reported that once cattle arrive at the feedlot, their overall appearance and health condition is the most influential factor in determining whether to administer metaphylaxis.

Transport distance or duration, animal body weight and age, source type (e.g., ranch versus sale barn), and geographic origin also ranked among the top considerations for veterinarians and managers when classifying animals in the medium-risk category. These responses are consistent with previous literature, which characterizes high-risk cattle as light weight, younger animals transported long distances and commingled from multiple sources (or markets), whereas lower-risk cattle are typically older, heavier, and sourced directly from a single (or few) operation(s) (Step et al., 2008; Taylor et al., 2010b; Wilson et al., 2017). In contrast, factors such as labor availability, cattle ownership, cost of the cattle, number of home pens, and concerns about antimicrobial resistance were reported to have little to no impact on metaphylaxis decisions.

Overall, veterinarians and managers demonstrated alignment in the criteria used to assess BRD risk and inform metaphylaxis decisions, criteria that are largely supported by the literature focused on best practices for animal health. Notably, both groups estimated that fewer than 15% of pens that they manage or consult for had metaphylaxis decisions driven primarily by economic considerations, such as purchase price or breakeven calculations. These findings suggest that, for most respondents, metaphylaxis decisions were driven primarily by animal health outcomes, rather than purely short-term economic incentives.

While health outcomes appeared to be the primary drivers of metaphylaxis decisions for most participants, economic considerations remain a critical component of sustainable cattle production. In particular, current markets which are characterized by historically high cattle prices and relatively low antimicrobial drug costs, may encourage a more liberal approach to metaphylaxis use. In 2023, nominal steer prices reached a record high, surpassing the previous peak from 2014, and are projected to continue rising through 2026 (Knight and Taylor, 2023; Williams et al., 2025). Although comprehensive historical data on antimicrobial pricing in livestock are limited, anecdotal evidence from feedlot professionals suggests that current drug prices are relatively low, likely due to increased availability of generic alternatives. In 2015, 52% of all animal drug approvals were for generic products (Sneeringer, 2019), and increased market competition following patent expirations likely contributed to lower prices. Additionally, the national sales and distribution of medically important antimicrobial drugs for food-producing animals have declined by 37% since 2015 (FDA, 2024a), which may have further contributed to lower prices through decreased demand (FDA, 2024b).

Veterinarians' estimates of the percentage of pens that did not receive metaphylaxis but, in hindsight, should have, remained consistent between historical and current periods. However,

there was an upward shift in the distribution of estimates for the current percentage of pens that received metaphylaxis but, in retrospect, may not have needed it, compared to historical estimates. This pattern provides some support for the hypothesis that current market conditions favor a more liberal application of metaphylaxis, where cattle at medium risk for BRD are more likely to be classified as high-risk. In open-text responses, some veterinarians indicated that rising drug costs (18%) and lower cattle prices (9%) are factors that, in their opinion, could lead to reduced metaphylaxis use. In contrast, managers' responses showed no clear difference in the distributions between historical and current estimates in either scenario, suggesting that their approach has remained consistent over time, despite changes in market conditions. The consistent responses from feedlot managers regarding metaphylaxis decisions over time, despite shifts in market conditions, likely suggest that their decision-making may be driven more by internal protocols, practical experience, and operation-specific outcomes than by external economic pressures. In contrast to veterinarians, whose broader exposure across multiple feedlots may make them more sensitive to industry trends such as rising cattle costs or declining drug prices, managers appear to rely on localized observations and established management strategies. This fixedness in metaphylaxis use may reflect a risk-averse approach aimed at maintaining operational continuity and minimizing disease-related disruptions, particularly in medium-risk cattle cohorts.

Several factors can be suggested to explain this shift in perception for reported higher historical (2018 to 2020) estimates compared to 2023 for both metaphylaxis "misses" (pens that should have received metaphylaxis but did not) and "overuses" (pens that received metaphylaxis but may not have needed it) by feedlot managers, and the high 2023 estimates compared to historical (2018 to 2020) estimates for "overuses" as indicated by veterinarians. These include

improvement in knowledge and decision-making tools over time, such as better diagnostics and risk assessment models; changes in economic pressure and incentives, particularly as high cattle prices in 2023 may have encouraged more targeted or more deliberate antimicrobial use; regulatory and market influences, including consumer-driven value-added programs like "No Antibiotics Ever"; and changes in cattle sourcing and risk profiles, which could have resulted in a different BRD risk landscape compared to five years ago.

This study employed a survey of U.S. feedlot veterinarians and managers to assess current knowledge and criteria related to BRD risk classification and metaphylaxis use in cattle at medium risk. Surveys are widely used in agricultural research to collect data on stakeholder beliefs, attitudes, and self-reported behaviors (Samuelson et al., 2016; Avemegah et al., 2021; Johnstone et al., 2021; Robles et al., 2021; Jumper et al., 2022; Dean et al., 2023; Edwards-Callaway et al., 2023). They serve descriptive and exploratory purposes, and are especially effective for gathering original data from populations too large or diffuse to observe directly (Babbie, 2020). Web-based questionnaires, in particular, offer advantages such as cost-effectiveness, convenience, absence of interviewer bias, direct data entry into electronic databases, and generalizability (when the study population of the surveys can be considered representative of the target population) (Stedman et al., 2019).

Despite their advantages, declining survey response rates have been well documented in recent decades and raise important concerns regarding generalizability of findings and the potential of nonresponse bias (Johansson et al., 2017; Stedman et al., 2019; Avemegah et al., 2021). Nonresponse bias can occur when the likelihood of participation is systematically related to variables of interest, which can distort survey estimates and reduce the validity of inferences made about the broader population (Peytchev, 2013; Wright, 2015). Since the strength of surveys

lies in their ability to generalize findings, systematic differences between respondents and the target population remain a critical consideration (Brehm, 2009; Goodfellow, 2023).

Although the number of responses was modest (25 veterinarians and 30 managers), participants represented an impactful share of the cattle feeding industry. Veterinarians reported that the total number of animals across all feedlots they consulted for in 2023 ranged from 10,000 to 2,000,000 animals, while participating managers collectively reported overseeing an one-time feedlot capacity of nearly 800,000 cattle. Although the survey questionnaire was disseminated nationwide through professional listservs, most respondents' feedlots were based in the Midwest and High Plains, regions that collectively account for the majority of U.S. feedlot capacities and beef production. This geographic pattern of participants and response rate has been reported in other surveys targeting other feedlot professionals, such as consulting nutritionists (Vasconcelos and Galyean, 2007; Samuelson et al., 2016). As such, while the findings from this survey may not fully reflect practices in less-represented regions of the U.S., the concentration of respondents from major cattle-feeding regions supports the relevance of the findings for the core of the U.S. feedlot industry.

Several factors have been proposed to explain declining participation in surveys. For instance, Babbie (2020) noted how the misuse of the term "survey" in spam or phishing attempts, such as telemarketing schemes disguised as legitimate surveys, has eroded public trust in research efforts. To help address these concerns and improve participation, we collaborated closely with the steering committee, composed of feedlot industry professionals, to promote the study, reinforce its legitimacy and relevance, and strengthen trust in the research intentions. While some have hypothesized that survey fatigue or burden (i.e., frequency, length, and content of past surveys) may deter participation, empirical research has found little evidence that these

factors alone drive nonresponse (McCarthy and Beckler, 2000; McCarthy et al., 2006). In contrast, concerns about data confidentiality and mistrust of data handlers appears to play a more significant role. Previous research has shown that privacy concerns and perceived risk-benefit ratio were associated with both reported willingness and actual participation in surveys (Singer et al., 1993; Singer et al., 2003) suggesting that it is not necessarily the actual risk of data disclosure, but rather the anticipated harm from such disclosure, that drives nonparticipation. These issues may be particularly relevant in the context of our study. Despite the anonymity of our questionnaire and absence of subject identifying information, antimicrobial use in animal agriculture remains a topic of intense scrutiny from consumers, media, and policymakers. Regulatory changes in the use of medically-important antimicrobial drugs to promote animal growth, coupled with heightened public debate surrounding antimicrobial resistance may have contributed to a greater perceived risk among potential respondents, especially when asked to share perspectives or practices related to metaphylaxis use in cattle at medium risk for BRD. This perceived risk could plausibly have influenced their decision not to participate or to respond conservatively. The tendency of respondents to provide socially desirable answers is known as social-desirability bias and has been found to affect the measurements of attitudes and self-reported behaviors (Fisher, 1993). These potential limitations aside, this survey yields valuable insight into the mindset and decision-making process of feedlot professionals and provides grounds for future hypothesis generation and research guidance.

Conclusion

This survey provides insight into how feedlot professionals approach the decision of whether to use metaphylaxis in cattle at medium risk for BRD. By contrasting the perspectives of veterinarians and feedlot managers, we identified consistencies and discrepancies in their

perceptions, information use, and the challenges associated with metaphylaxis decisions for these cattle cohorts. These findings highlight critical information gaps that, if addressed, could advance antimicrobial stewardship in feedlot systems. Results indicate that future research opportunities include: (1) enhancing data-driven BRD risk assessment through improved collaboration and information sharing across the production chain and (2) defining risk-factor prioritization for metaphylaxis decision-making in medium risk cattle. Specifically, determining which risk factors should be weighed more heavily when cattle present both high- and low-risk characteristics (e.g., a scoring system to support a more refined assessment of metaphylaxis need in medium risk cattle). The knowledge gained from this work, gathered directly from professionals actively engaged in managing BRD, can inform the development of targeted strategies to improve risk classification, optimize antimicrobial use, and support better health outcomes for feedlot cattle. Ultimately, this research contributes to the broader goal of sustainable beef production by promoting judicious antimicrobial use while safeguarding animal health and welfare.

Funding

The author(s) declare that financial support was received for the research, authorship, and publication of this article. Financial support was provided by the Foundation for Food and Agriculture Research through the International Consortium for Antimicrobial Stewardship in Agriculture (Grant #22-000459), the Center for Outcomes Research and Epidemiology, and the College of Veterinary Medicine at Kansas State University.

Acknowledgments

The authors extend their appreciation to the steering committee members who provided valuable guidance throughout this project. Members included representatives from Innovative

Livestock Services (Beef Alliance), Hy-Plains Feedyard, Veterinary Research and Consulting Services (VRCS), Five Rivers (Beef Alliance), Zoetis, and Cactus Feeders, as well as other industry partners.

Conflict of Interest

The authors declare no conflict of interest.

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Tables and Figures

Table 3.1. Characteristics of feedlot operations and cattle population demographics represented in the questionnaire administered to consulting feedlot veterinarians

Item [§]	Responses, n	Mean	Median	IQR	Range
Feedlot Operations Characteristics					
Smallest feedlot size, one-time animal capacity, n	20	2,457	1,000	450 – 2,500	80 – 15,000
Largest feedlot size, one-time animal capacity, n	21	59,429	65,000	20,000 – 85,000	5,000 – 130,000
Summary of all animals in all feedlots, n	21	452,333	300,000	100,000 – 800,000	10,000 – 2,000,000
Percentage of cattle by ownership					
Exclusively by customer	24	33	25	9 – 50	0 – 100
Exclusively by the feedlot	24	42	38	8 – 72	0 – 100
Jointly by the feedlot and customer	24	9	4	0 – 12	0 – 33
Cattle Demographics					
Percentage of cattle by age category					
Calves	22	47	40	21 – 78	10 – 90
Yearlings	22	50	58	22 – 68	10 – 90
Others	22	3	0	0 – 4	0 – 35
Percentage of cattle by sex category					
Steers	22	53	60	50 – 62	15 – 90
Bulls	22	10	1	0 – 9	0 – 50
Heifers	22	34	35	30 – 40	0 – 60
Spayed heifers	22	2	0	0 – 3	0 – 10
Percentage of cattle by breed category					
Beef breeds	22	82	83	70 – 90	60 – 100
Dairy breeds	22	3	1	0 – 3	0 – 20
Beef-on-dairy cross	22	15	15	5 – 22	0 – 40
Percentage of cattle by origin					
U.S.	22	88	97	86 – 100	0 – 100
Canada	22	2	0	0 – 1	0 – 20
Mexico	22	5	0	0 – 8	0 – 40

[§]IQR = Interquartile range; n = number. Percentages refer to the proportion of all cattle veterinarians consulted for in 2023 which fell into each category.

Table 3.2. Characteristics of feedlot operations and cattle population demographics represented in the questionnaire administered to feedlot managers

Item [§]	Responses, n	Mean	Median	IQR	Range
Feedlot Operations Characteristics					
Feedlot size, one-time animal capacity*, n	27	29,550	24,000	2,100 – 50,000	500 – 120,000
Home pens, n	27	202	209	15 – 375	2 – 600
Minimum pen sizes, animals/pen [∞]	27	70	50	38 – 71	1 – 350
Maximum pen sizes, animals/pen [∞]	27	299	300	200 – 350	120 – 1,000
Percentage of cattle by ownership					
Exclusively by customer	29	38	30	0 – 80	0 – 100
Exclusively by the feedlot	30	46	50	1 – 84	0 – 100
Jointly by the feedlot and customer	30	7	5	0 – 10	0 – 25
Cattle Demographics					
Percentage of cattle by age category					
Calves	30	45	45	15 – 74	0 – 100
Yearlings	30	44	40	15 – 80	0 – 98
Others	29	4	0	0 – 0	0 – 60
Percentage of cattle by sex category					
Steers	30	54	55	43 – 65	0 – 100
Bulls	29	3	0	0 – 0	0 – 35
Heifers	30	32	33	20 – 50	0 – 75
Spayed heifers	30	4	0	0 – 4	0 – 25
Percentage of cattle by breed category					
Beef breeds	30	75	90	65 – 100	0 – 100
Dairy breeds	30	3	0	0 – 0	0 – 60
Beef-on-dairy cross	30	15	4	0 – 19	0 – 80

[§]IQR = Interquartile range; n = number. Percentages refer to the proportion of cattle from managers' feedlots that fell into each category.

*One participant reported a feedlot one-time capacity of 1. The entry was assumed to be an entry error or misinterpretation of the question and therefore was deleted for the computation of the summary statistics.

[∞]One participant reported a 45,000 animal-capacity for the minimum pen size in their feedlot, and 60,000 animal-capacity for the maximum pen size in their feedlot. These entries were assumed to be an entry error or misinterpretation of the survey question and therefore were deleted for the computation of the summary statistics.

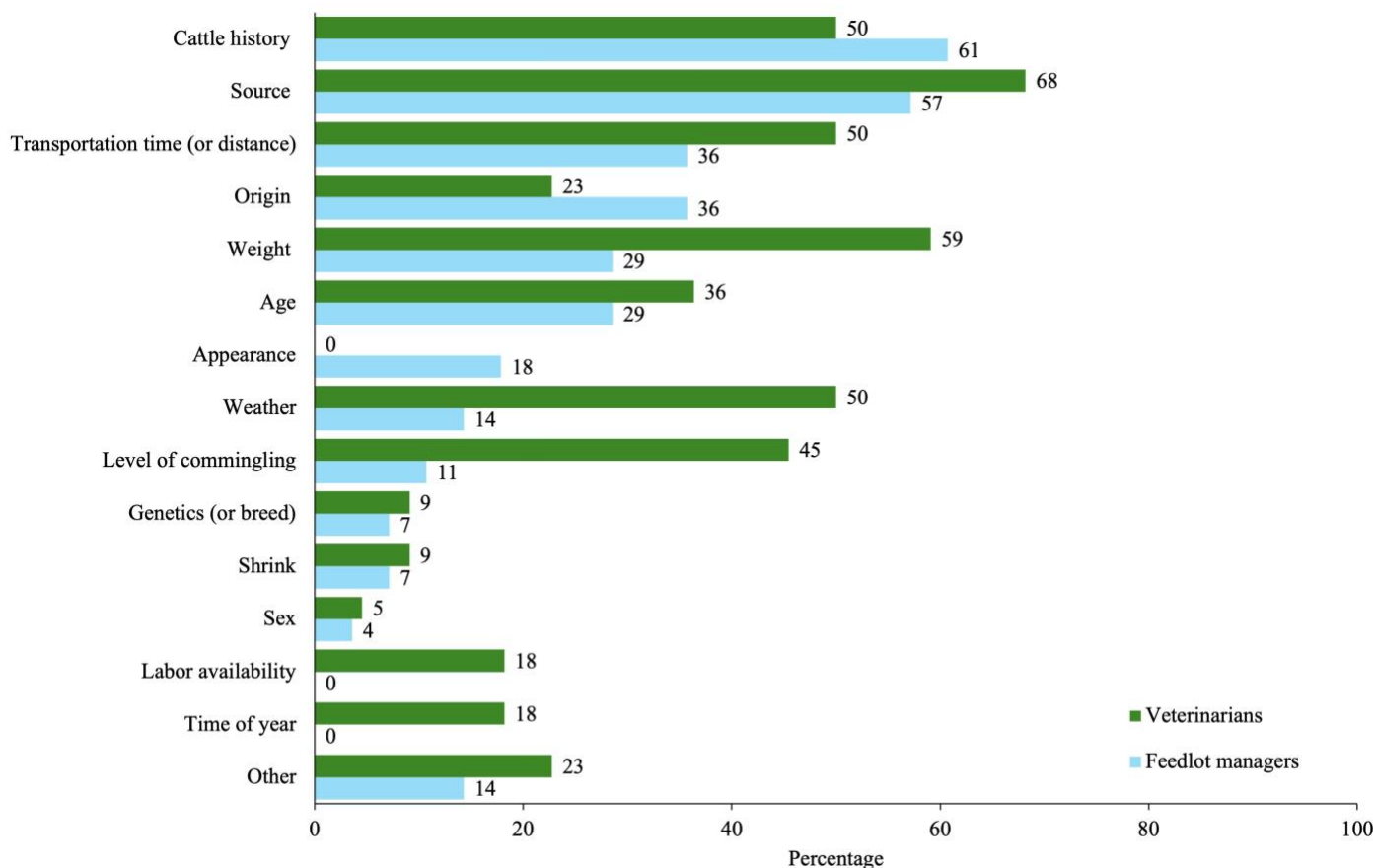


Figure 3.1. Frequency distributions of categorized criteria used by surveyed veterinarians (top bar) and feedlot managers (bottom bar) to classify cattle at medium-risk for bovine respiratory disease (bars ordered by the highest percentage of mentions from feedlot managers).

Percentages were calculated from the open-text responses of 22 veterinarians and 28 managers. Numbers at the end of each bar represent the percentage of respondents who described factors related to each of the listed criterion in open-text responses, which were grouped into broader categories. “Other” includes factors mentioned only once, such as “*dust, pregnancy risk, new arrivals, unforeseen event (i.e., truck break down), client's husbandry practices, cost of cattle, and post processing morbidity*”.

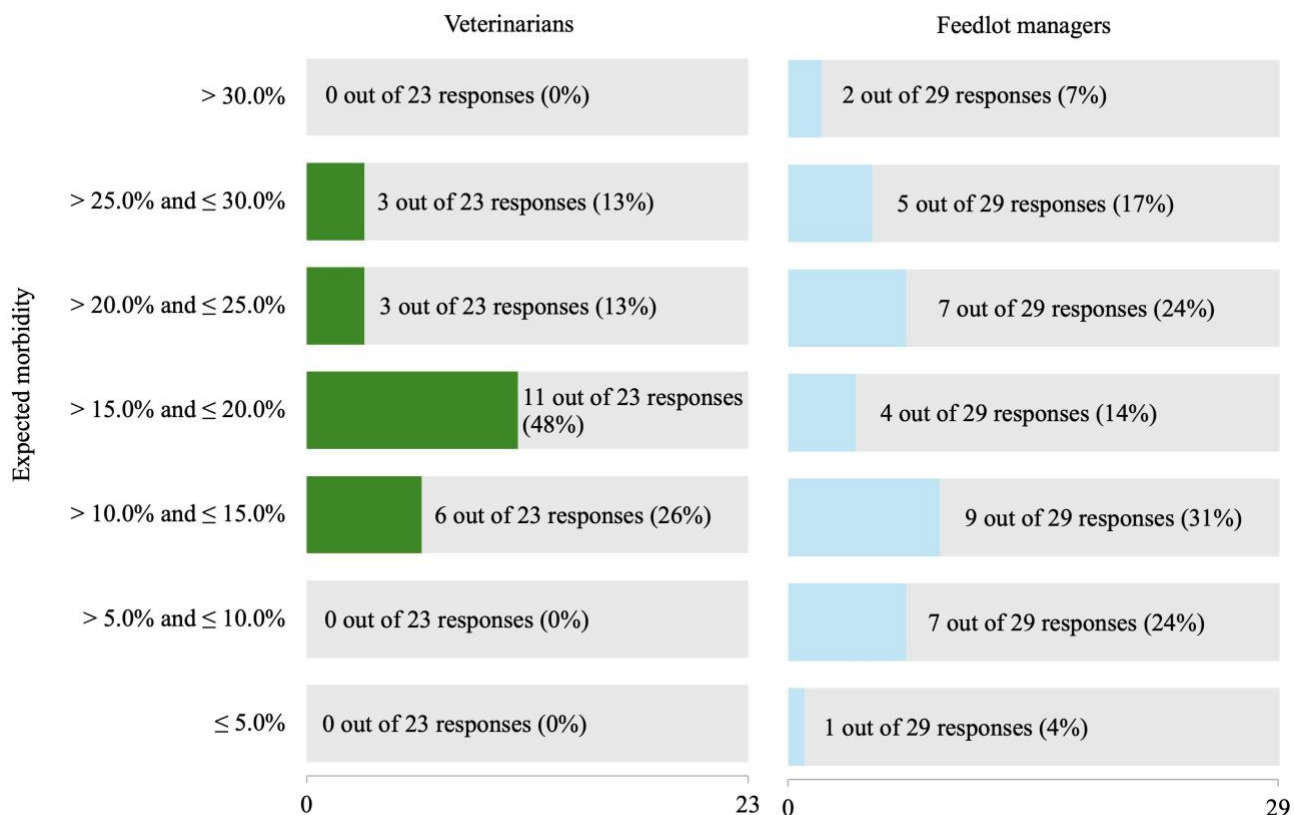


Figure 3.2. Veterinarians (left panel) and feedlot managers (right panel) expected morbidity in cattle cohorts at medium-risk for bovine respiratory disease (BRD).

Respondents were allowed to select more than one response from the multiple-choice format list of expected ranges.

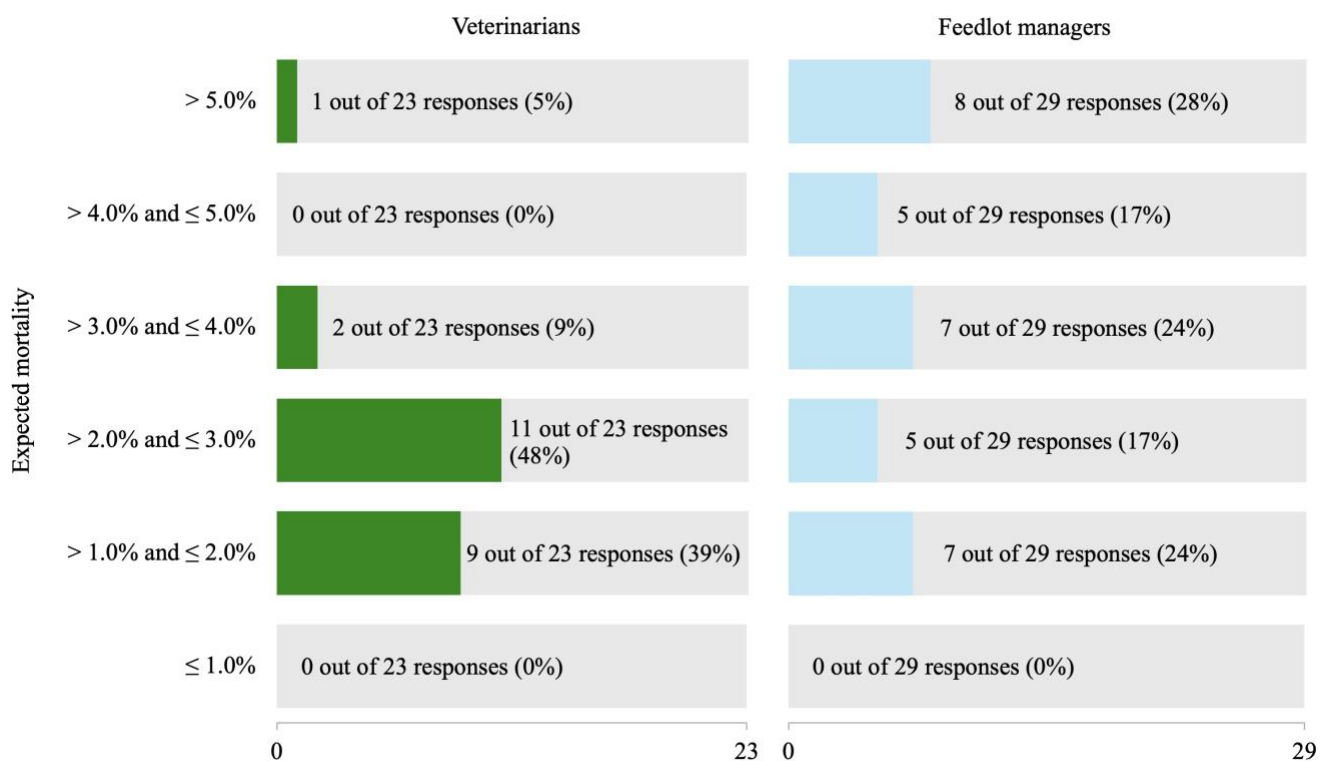


Figure 3.3. Veterinarians (left panel) and feedlot managers (right panel) expected mortality for cattle at medium-risk for bovine respiratory disease.

Respondents were allowed to select more than one response from the multiple-choice response format of expected ranges.

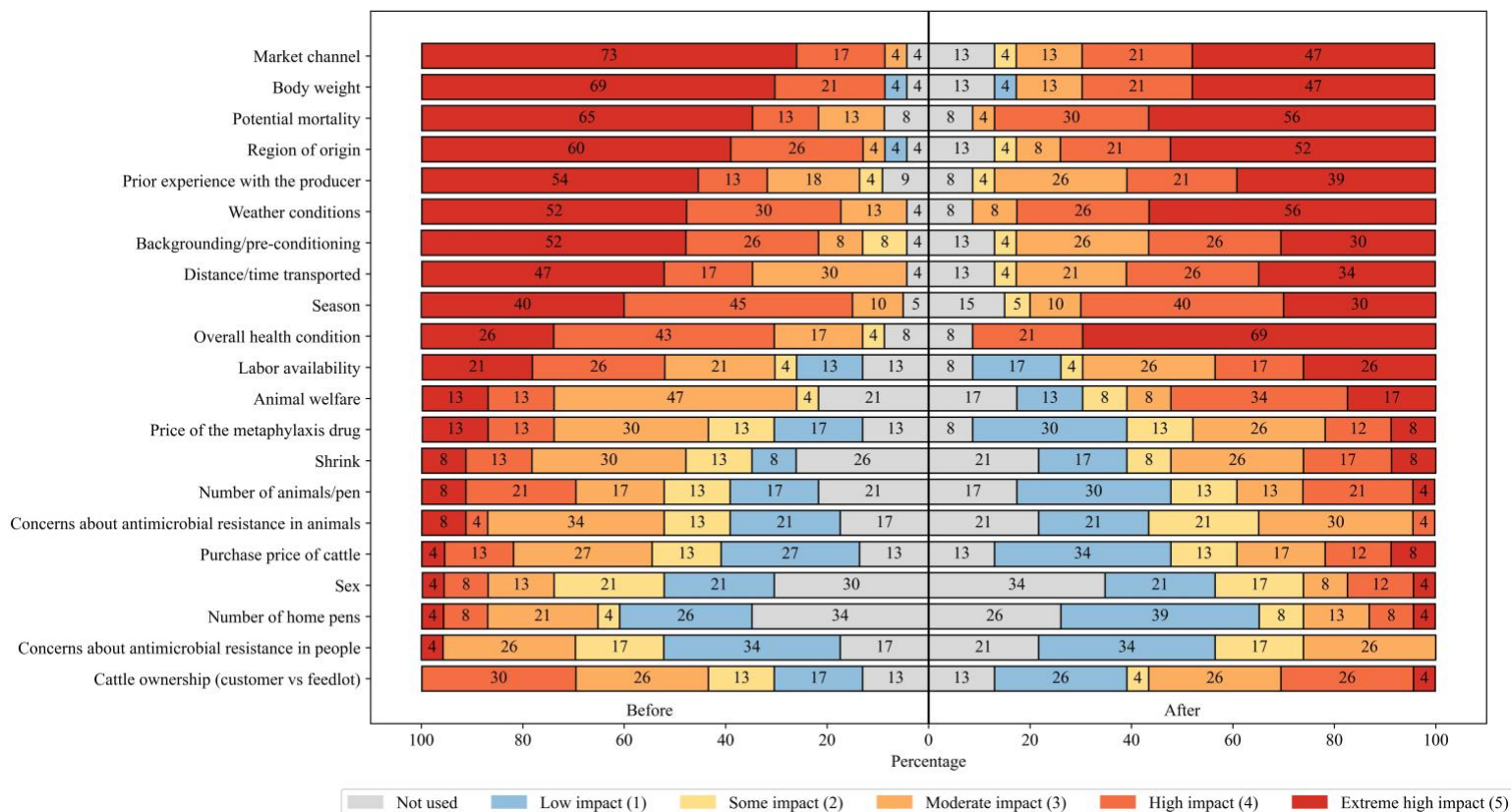


Figure 3.4. Veterinarians’ perspectives on the impact of various factors on the decision to administer metaphylaxis to cattle at medium-risk for bovine respiratory disease, before (left-hand side) and after (right-hand side) arrival at the feedlot.

Numbers within the bars represent the percentage of respondents (calculated out of 23 total veterinarians) who selected each impact level (e.g., no, low, moderate, or high impact) for each factor proposed in a multiple-choice Likert-scale response format. Factors affecting metaphylaxis decisions are ordered by the percentage of respondents who rated each as “extreme high importance” before cattle arrival, with those selected by the largest percentage listed at the top.

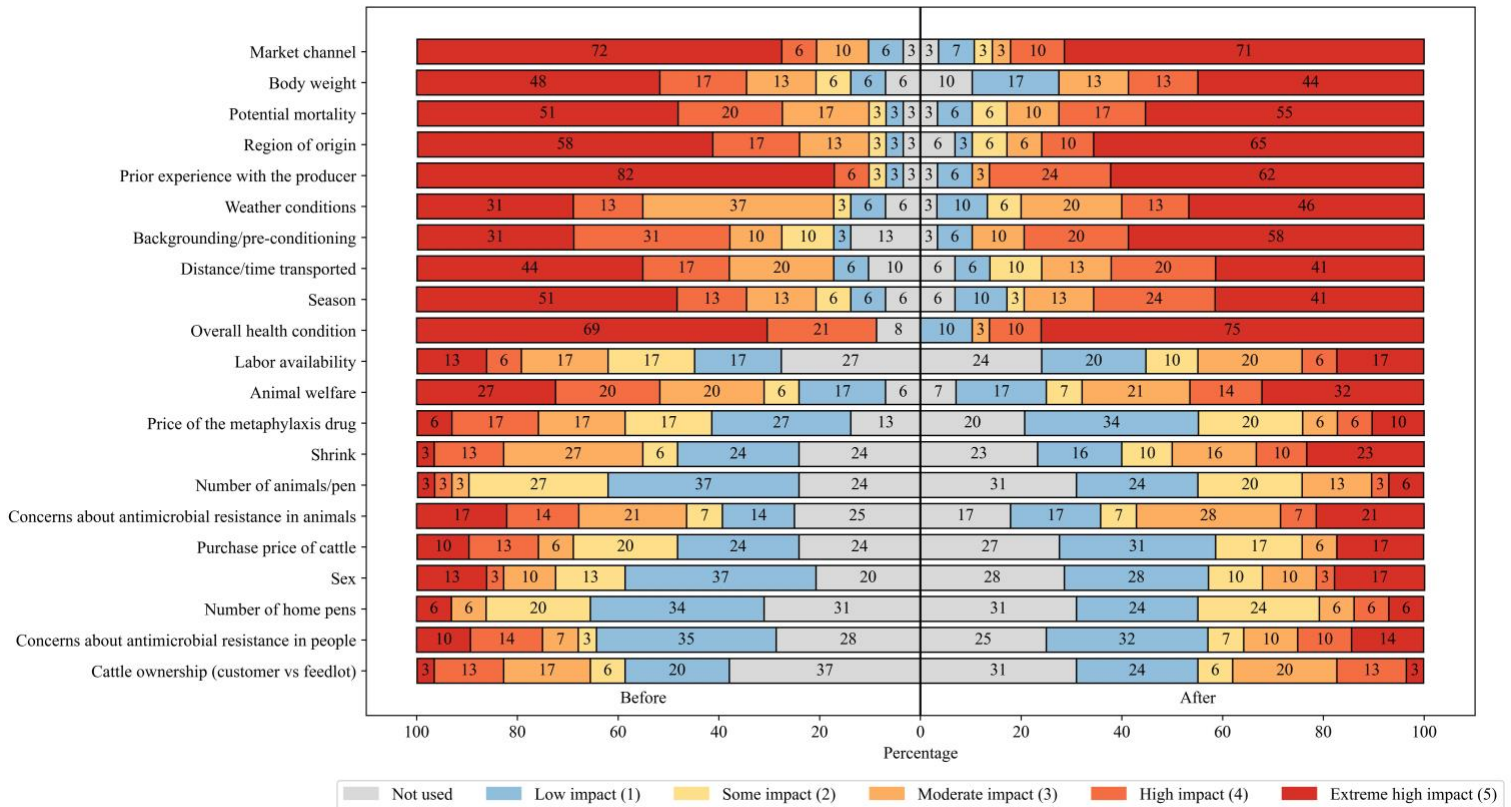


Figure 3.5. Feedlot managers’ perspectives on the impact of various factors on the metaphylaxis decision for cattle at medium-risk for bovine respiratory disease, before (left-hand side) and after (right-hand side) arrival at the feedlot.

Numbers within the bars represent the percentage of respondents (calculated out of 29 total managers) who selected each impact level (e.g., no, low, moderate, or high impact) for each factor proposed in a multiple-choice Likert-scale response format. Factors affecting metaphylaxis decisions are ordered based on veterinarians’ responses (for ease of comparison), according to the percentage who rated each as “extreme high importance” before cattle arrival, with those selected by the largest percentage listed at the top.

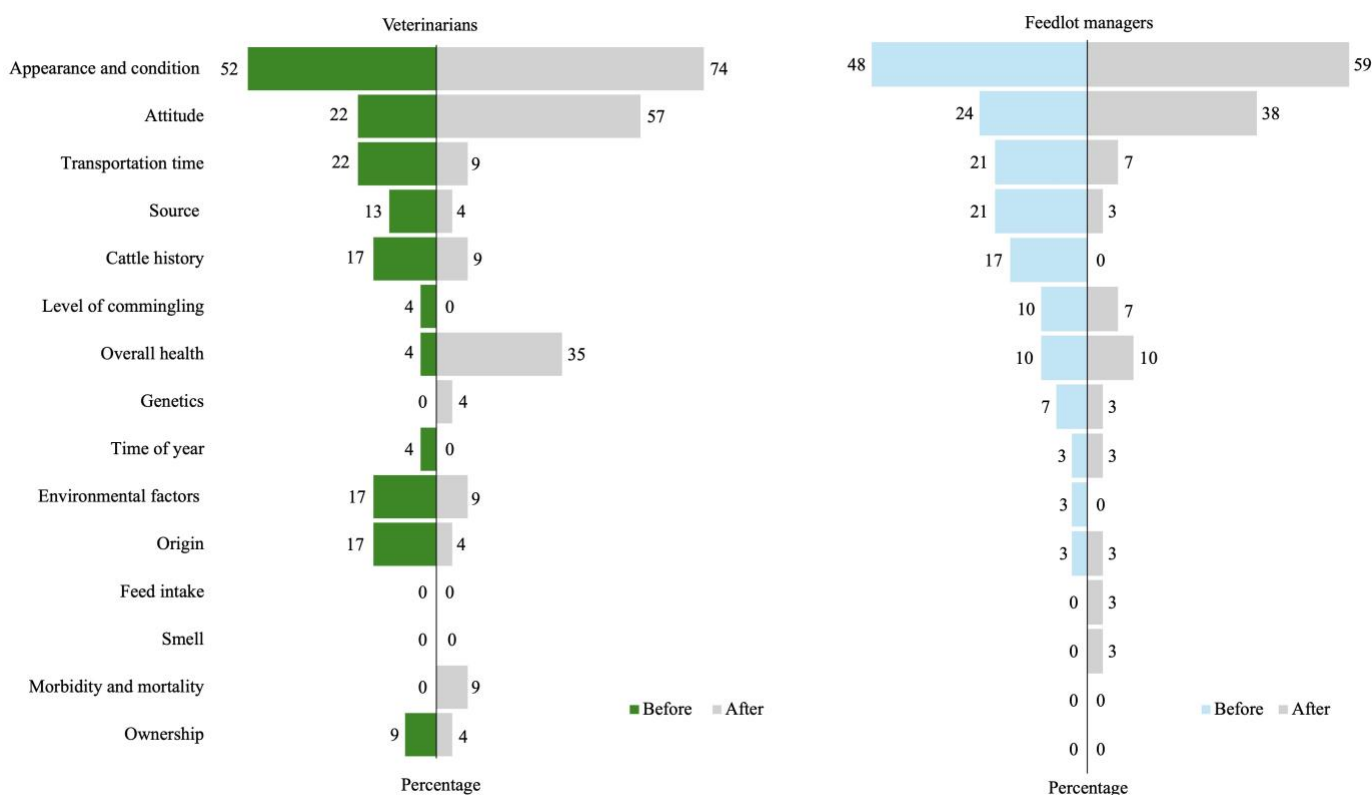


Figure 3.6. Frequency distributions of “Other” categorized criteria (aside from those listed in Figures 4 and 5) used by surveyed veterinarians (left-hand side) and feedlot managers (right-hand side) to guide metaphylaxis decisions for cattle at medium-risk for bovine respiratory disease, both before (left-side bars) and after (right-side bars) cattle arrival at the feedlot (bars ordered by the highest percentage of mentions from feedlot managers before cattle arrival). Numbers at the end of each bar represent the percentage of respondents who mentioned each criterion as an “Other” open-text response format, which were grouped by theme into broader categories. Percentages were calculated out of 23 total veterinarians’ and 29 managers’ responses. Among veterinarians who participated, 30% (7) and 17% (4) left the open-text field blank for before and after cattle arrival at the feedlot, respectively. Among managers who participated, 31% (9) and 34% (10) left the open-text fields blank for before and after cattle arrival at the feedlot, respectively.

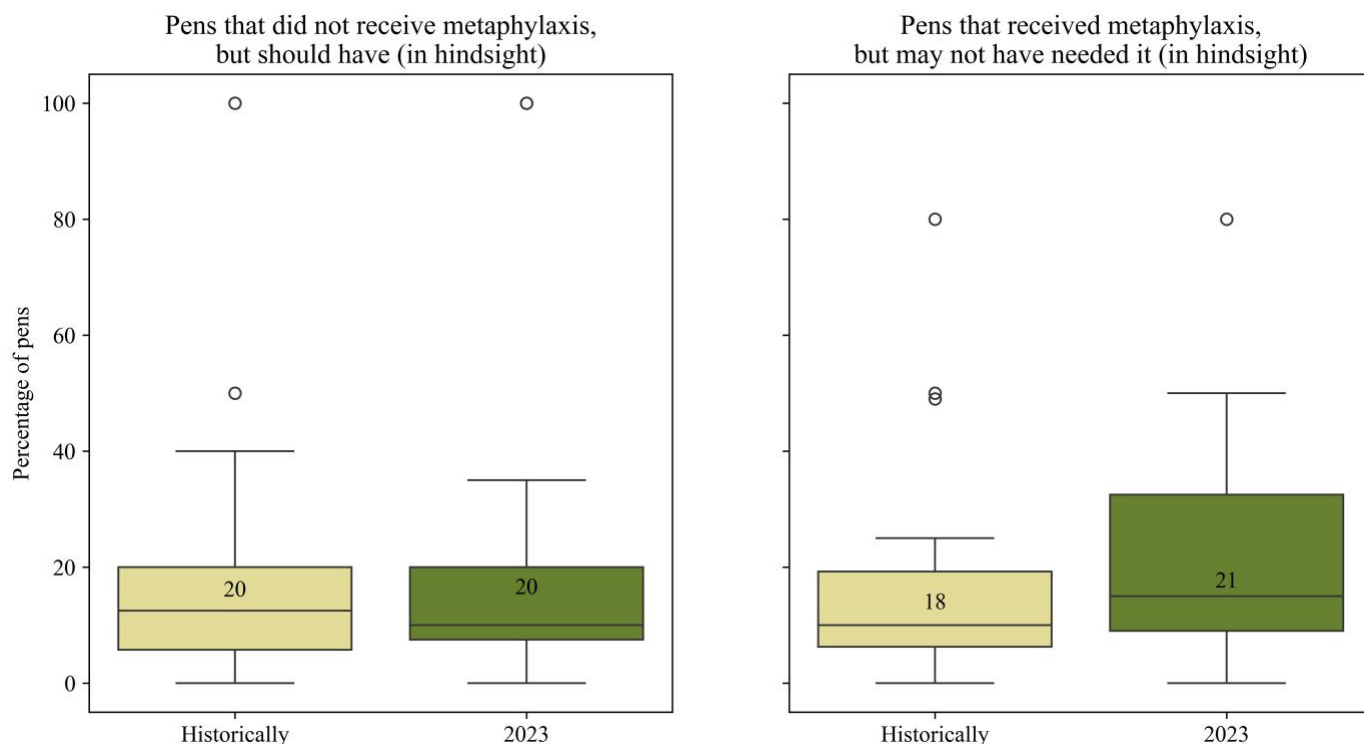


Figure 3.7. Boxplots depicting veterinarians’ perceptions of metaphylaxis use for bovine respiratory disease in 2023 compared to historical use (between 2018 and 2020).

The left panel displays the reported percentage of pens that did not receive metaphylaxis at feedlot arrival but, in hindsight, should have been treated. The right panel displays the reported percentage of pens that did receive metaphylaxis but, in hindsight, may not have needed it. Each boxplot shows the interquartile range (IQR; 25th to 75th percentile) as the box, the median (50th percentile) as the horizontal line within each box and whiskers extend to the minimum and maximum values within 1.5 times the IQR. Individual outliers beyond the whiskers are shown as dots in the plot, and mean values (percent of pens) are displayed as labeled points. Results were summarized from 23 open-text, numerical responses.

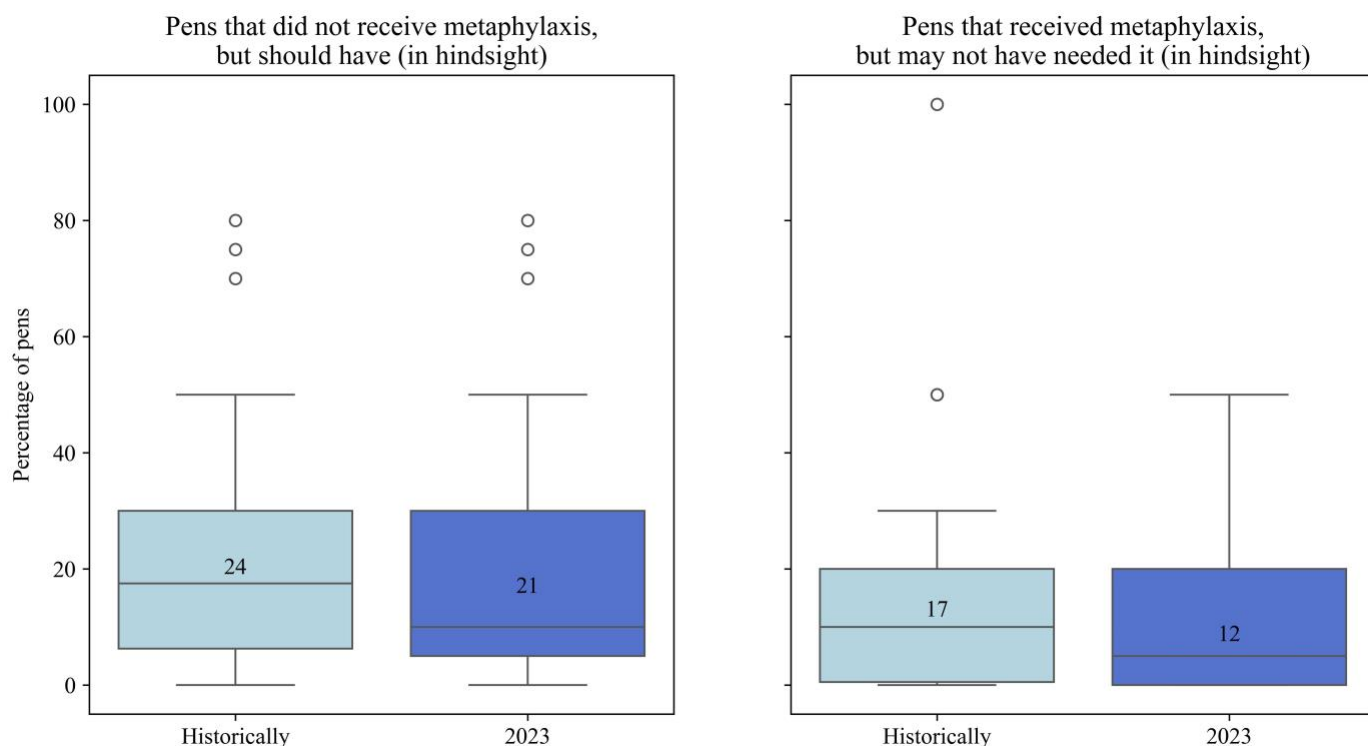


Figure 3.8. Boxplots depicting feedlot manager perceptions of metaphylaxis use for bovine respiratory disease in 2023 compared to historical use (between 2018 and 2020).

The left panel displays the reported percentage of pens that did not receive metaphylaxis at arrival but, in hindsight, should have been treated. The right panel displays the reported percentage of pens that did receive metaphylaxis but, in hindsight, may not have needed it. Each boxplot shows the interquartile range (IQR, 25th to 75th percentile) as the box, the median (50th percentile) as the horizontal line within each box, and whiskers extend to the minimum and maximum values within 1.5 times the IQR. Individual outliers beyond the whiskers are shown as dots in the plot, and mean values (percent of pens) are displayed as labeled points. Results were summarized from 27 open-text, numerical responses.

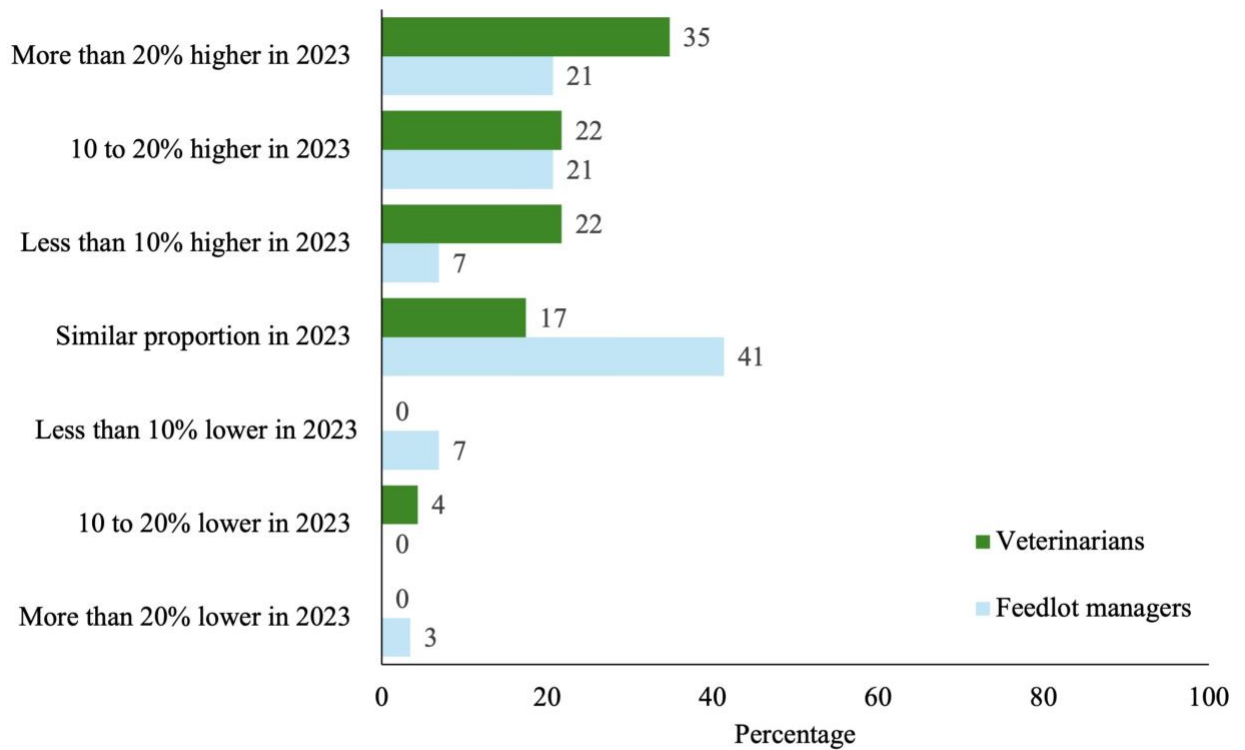


Figure 3.9. Veterinarians (top bar) and feedlot managers (bottom bar) estimates of how the proportion of feedlot pens receiving metaphylaxis in 2023 compares to 3 to 5 years ago (e.g., during 2018 to 2020).

Percentages were calculated from 23 veterinarians' and 29 feedlot managers' responses.

Numbers at the end of each bar indicate the percentage of respondents who selected the proposed option in a multiple-choice response format. Respondents were only allowed to select one response.

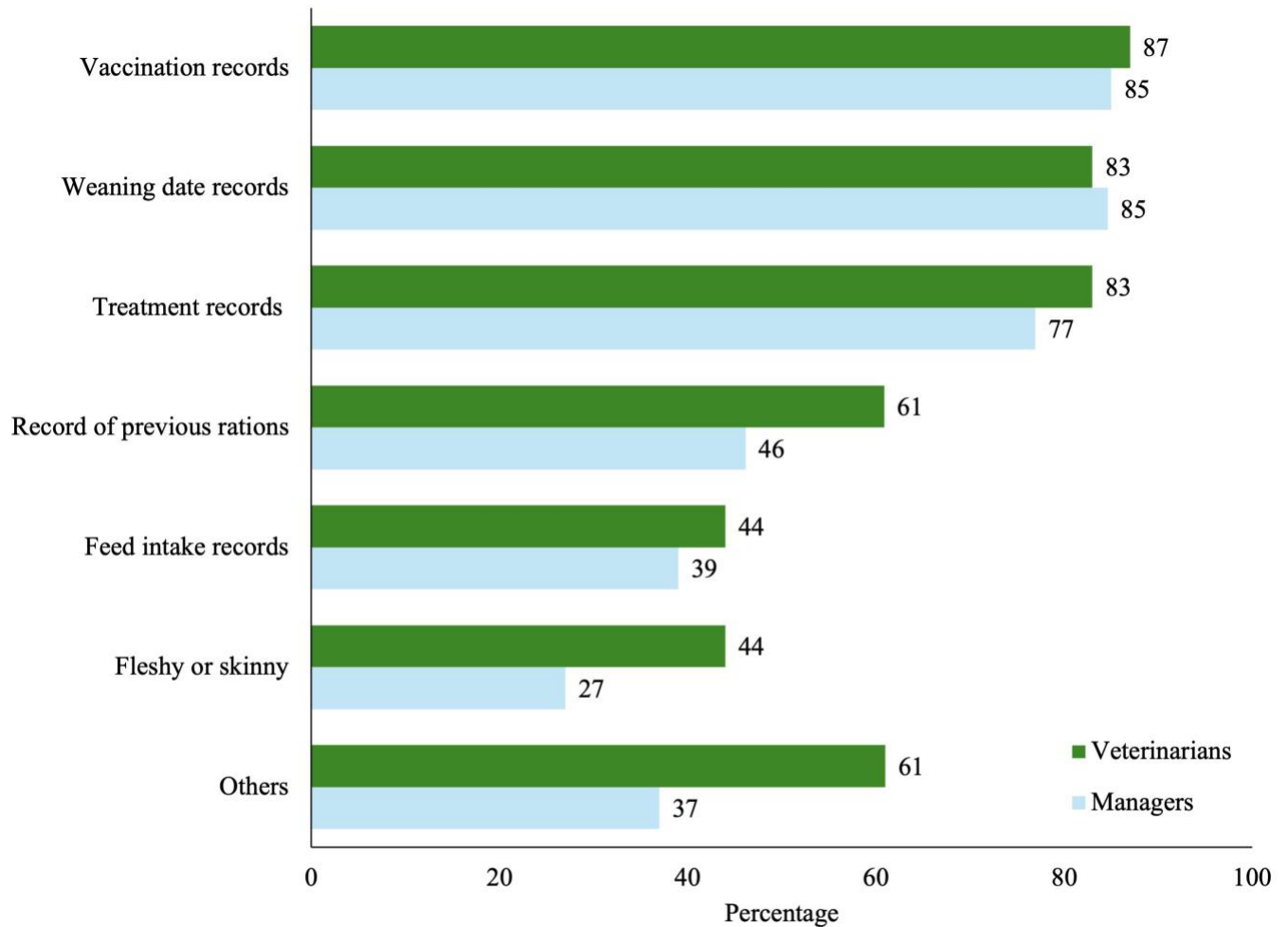


Figure 3.10. Subjective and objective information veterinarians (top bar) and feedlot managers (bottom bar) wish they had more often or with greater accuracy when deciding whether to use metaphylaxis in cattle at medium-risk for bovine respiratory disease (bars ordered by the highest percentage of mentions from feedlot managers).

Percentages were calculated from 23 veterinarians' and 27 managers' responses. Numbers at the end of each bar represent the percentage of respondents who selected a proposed criterion in a multiple-choice response format. "Others" includes additional criteria suggested as an open-text response format, such as, "*dewormer, implants, number of pens/locations they came from, origin, level of commingling, source (e.g., from sale barn or direct from ranch), proprietary, system grown (i.e., wheat pasture, grow yard), stale, stress, morbidity, mortality, mother condition, how long animals were at sale barn, previous performance history, previous system,*

daily gain, backgrounding days, weather prior to shipping, previous handling, dairy steers, and backgrounded commingled bulls and steers.”

Chapter 4 - Effects of combining value-added programs on sale prices of calf lots sold through the Superior Livestock Auction

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(Published in *Applied Animal Science*, 2025, 41:252-264. doi:10.15232/aas.2024.02638)

Abstract

Objective(s): (1) estimate sale prices of calf lots sold through the Superior Livestock Auction (SLA) with different combinations of value-added program claims (COMBO), and (2) compare results from two models for estimating prices.

Materials and Methods: data included lots of heifers, steers, or mixed-sex calves, averaging 113 to 365 kg, sold from 50 to 300 US\$/45.4 kg, containing 5 to 5,000 home-raised, non-breeding animals of U.S. origin. Holstein and Holstein-mixed breed, and feeder lots were excluded. Sale channels included country page, internet, private treaty, or video sales. Linear

mixed models estimated effects of value-added programs (VAP) for vaccination protocols (VAC24, VAC34(+), VAC45(+), VAC60), non-hormone treated cattle (NHTC), Beef Quality Assurance (BQA), and Global Animal Partnership (GAP), on sale prices, controlling for sex, weight, region, and sale month.

Results and Discussion: Data from 12,158 calf lots sold through SLA in 2019 and 2020 were analyzed. Prices were significantly associated with VAP combination, but dependent on sex [sex $\times$ COMBO; $P < 0.01$]. Region and weight also significantly affected sale prices ($P > 0.01$). Calf lots with VAC45, NHTC, with or without BQA, and GAP received the highest prices, while VAC24-only, VAC34-only, and VAC34 with BQA (no NHTC or GAP) received equal or lower prices than no-VAP, regardless of sex. Both regression models supported similar interpretations when considering these specific VAP combinations.

Implications and Applications: Understanding the marginal impacts of VAP combinations may help producers make informed decisions for profitable management and marketing strategies. Producers should consider whether expected VAP premiums outweigh added costs.

Key words: Beef calves, Marketing, Premiums, Superior Livestock Auction, Value-added programs

Introduction

The Superior Livestock Auction (SLA) is a company that offers video and internet auction services for livestock marketing across North America. Livestock auction markets, including the SLA, have established several value-added programs (VAP) designed to accentuate

the value of calves raised under specific management standards. These programs serve as a bridge between marketplace preferences and production: consumer demand for particular product characteristics drives the creation of VAP, while these programs guide producers to align with current market preferences. Value-added marketing involves increasing a commodity's worth through effective management techniques and promoting it in a way that compensates for the additional costs generated. If the adoption of a value-added activity does not increase the overall profitability for the producer, it is unlikely there will be wide adoption in the supply chain.

The objectives of this study were twofold: first, to estimate and evaluate sale prices associated with calf lots sold through the Superior Livestock Auction (SLA) market, claiming different selected VAP combinations (COMBOs), and second, to compare results from two different regression models used to estimate these sale prices. To estimate the sale price associated with adopting VAP, alternative methods can be applied. One method may estimate and compare price premiums by calculating the average payout per lot for those with a specific VAP versus those without, assuming the effects of each VAP on lot prices are independent. Alternatively, one could argue that VAP implemented in a particular lot may have interdependent effects on the sale prices, meaning that evaluating specific combinations of VAP may be more appropriate to estimate price rather than each VAP independently. By evaluating these objectives, we aim to assist cow-calf producers by providing insights into the anticipated returns from implementing specific short-run VAP that can be immediately applied to their current calf lot. The findings also may offer value to cattle feeders regarding premium expectations during procurement. By providing a comprehensive understanding of the potential benefits associated with specific VAP combinations, we aim to empower stakeholders in the

cattle industry to make strategic and economically sound decisions, fostering more informed and successful livestock management approaches.

Materials and Methods

Data

Data on U.S. sale transaction information related to calf lots were used for this analysis. A “lot” is defined as a single cohort of animals from the same origin, which is the unit of sales transaction. The dataset was derived from an original set containing 28,972 records on sales of calf and feeder cattle lots through the SLA market, spanning from January 2019 through December 2020. No human or animal subjects were used, so this analysis did not require approval by an Institutional Animal Care and Use Committee or Institutional Review Board.

Eligibility criteria

Inclusion criteria for the final dataset considered for this analysis consisted of calf lots of heifers, steers, or both (“mixed”), weighing between 113 and 365 kg (250 and 800 lb), sold for more than \$50/45.4 kg and less than \$300/45.4 kg (US dollars; 45.4 kg = 100 lb), containing a range of 5 to 5,000 animals of nonbreeding type, that were home raised (i.e., born and raised in the same farm), and of U.S. origin. Sale transaction channels included country page sales, internet sales, private treaty, or video sales. Holstein, Holstein-mixed breed, and feeder calf lots were excluded from this analysis.

VAP and data management

Four frequently claimed VAP, which were viable program-options for short-run implementation in an existing or future lot of calves (as opposed to a long-run change that could take years to implement), and which were consistently reported by the consignor in a designated data-entry field (as opposed to entering information in comments and other open-text field

options), were identified through construction of a frequency table of all SLA VAP programs. Table 4.1 shows the list of all SLA VAP programs available in the dataset and their respective frequencies in lot claims. Full descriptions of each program can be found at <https://superiorlivestock.com/value-added-programs>. In brief, the different vaccination (VAC) certifications are preconditioning programs intended to enhance calf health and market readiness that specifies inclusion and timing of weaning and administration of a series of vaccines and internal and external parasite controls at specified intervals before shipping or delivery. The programs progress in complexity and timing, starting with VAC24, which requires calves to be vaccinated on the cow at 2 to 4 months of age with a single dose of the key vaccines. The next level, VAC34, requires calves to be vaccinated on the cow 3 to 4 weeks before shipping with the key vaccines, in addition to receiving a dose of 7-way, 8-way, or 9-way clostridial vaccine at branding; VAC34+ builds on VAC34 by requiring the same vaccinations, with an additional dose of viral 5-way vaccine (comprising infectious bovine rhinotracheitis, parainfluenza 3, bovine respiratory syncytial virus, and bovine viral diarrhea types 1 and 2) administered at branding. The VAC45 program requires calves to be vaccinated twice with the key vaccines: first at branding or 2 to 4 weeks before or at weaning, followed by a booster given according to vaccine label instructions. Calves must also be home raised and weaned for a minimum of 45 days before delivery. VAC45+ builds on VAC45 requirements by mandating 3 rounds of vaccination with the key vaccines: at branding, 2 to 4 weeks before or at weaning, and again as a booster per label instructions. In addition, calves must receive both internal and external parasite control and be home raised and weaned for a minimum of 45 days before delivery. Last, VAC60 has similar requirements to VAC45+, but calves must be weaned for a minimum of 60 days before delivery. Key vaccines include a 7-way, 8-way, or 9-way clostridial vaccine; a viral 5-

way vaccine; and a *Mannheimia haemolytica*, *Pasteurella multocida*, or both vaccines. Parasite control is recommended when not explicitly required. Beef Quality Assurance (BQA) certification is a national program that provides guidelines for cattle handling, feeding, and management to ensure the production of high-quality, safe beef, thereby increasing consumer confidence. The non-hormone-treated cattle (NHTC) certification refers to cattle that have been raised without the use of synthetic hormones, whereas Global Animal Partnership (GAP) is a third-party certification program that emphasizes and verifies compliance with humane and sustainable practices, allowing producers to differentiate their cattle crop based on greater animal welfare standards. Key factors evaluated by auditors include the proportion of lifetime spent on pasture, access to an enriched environment (e.g., shade or shelter), specific maximum transport times, a specified maximum age for castration, and a minimum age for weaning.

A hypothesized challenge with the analysis of VAP, is that considering these programs as independent may not fully account for the combined effect of multiple VAP claims on the sale value of a lot. For example, classifying each VAP as an independent fixed effect in a multivariable model would imply that effects on price are additive, indicating that calf prices may increase by the same magnitude for each sequential VAP that is added to a lot. In reality, there may be diminishing returns as more programs are added, and multicollinearity between programs could exist, as some may frequently occur only when in the presence of others. It may be more appropriate to combine VAP into unique combinations of programs, to better evaluate their cumulative effects, rather than assuming they affect price changes independently or additively. Therefore, by evaluating the effect of specific VAP combinations (i.e., treating a combination of programs as a single explanatory variable), a more comprehensive assessment of their overall economic impacts may be made.

The VAC programs, BQA, NHTC, and GAP were selected from the VAP list for the analysis of associations between all possible combinations of these selected VAP, and the sale price of calf lots. During 2019 and 2020 sales, the SLA services allowed selection of 1 of 7 VAC options: VAC24, VAC34, VAC34+, VAC45, VAC45+, VAC60, and VAC PRECON. For all analyses, lots claiming VAC34 and VAC34+ were collapsed into a single group “VAC34.” Similarly, lots that claimed VAC45 and VAC45+ were collapsed into a single group “VAC45.” Only VAP reported in the designated field were considered (i.e., any reporting of VAP in a comments field was not considered). The selected VAP were used to create a single explanatory variable (i.e., a COMBO variable of covariate patterns across the VAP) containing patterns for all possible combinations of the 4 frequently claimed VAP.

Levels of the COMBO variable included the unique combination of 1 of the 5 possible VAC programs, 1 of the 2 possible BQA claims, 1 of the 2 possible NHTC claims, and 1 of the 2 possible GAP claims, comprising a total of 40 possible combinations ($5 \times 2 \times 2 \times 2$). For example, a lot that was sold as VAC34, and was not NHTC, not BQA, and not GAP, would be classified as VAC34-0-0-0 in the COMBO variable, a unique category for the combination of those variables. Thirty-four of the 40 possible combinations were claimed at least once by calf lots sold during 2019 and 2020. Frequencies of COMBO claims for calf lots sold via the SLA during the reported timeframe are presented in Table 4.2. Combinations of VAP that were claimed in more than 1.0% of the calf lots, as depicted in Table 4.2, were included as a COMBO category in this analysis. Patterns of COMBO occurring in less than 1.0% of the calf lots were collapsed into an “other” category for the purpose of this analysis.

Statistical analysis

Prices associated with the combination of VAP were estimated via 2 different regression models. The difference between the 2 models relates to the structure of the independent variables. Although the explanatory variables for sale price of lots were the same, the ability to independently estimate price for each variable was considered differently in each of the 2 models. In the first model (the COMBO model), the selected VAP were collapsed into a single explanatory variable, COMBO, with categories comprised of the unique combinations of the selected VAP (rather than evaluating each VAP independently), yielding a unique parameter for each observed combination of VAP. In the second model (the VAP model), each of the selected VAP were included as an independent variable (i.e., VAC, NHTC, BQA, and GAP were each specified as standalone explanatory variables). Specification of additional covariates was identical between the 2 models.

Both assessments employed a multivariable linear mixed model using a Gaussian distribution, identity link function, and a statistical significance threshold of $\alpha \leq 0.05$ using the GLIMMIX procedure of SAS (version 9.4; SAS Institute Inc., Cary, NC) for analysis. The 2 multivariable linear mixed models were fitted to evaluate the effects of the selected VAP (VAC [VAC24, VAC34, VAC45, VAC60], NHTC, BQA, and GAP) on calf lot sale price (\$/45.4 kg), while controlling for lot average weight, sex, U.S. region, and month of sale. These covariates (sex, weight, and U.S. region of sale) were specified and included identically in the 2 models. An assessment of multicollinearity was conducted using the Pearson correlation matrix of the fixed-effects parameter estimates, which if present, was defined as having an absolute correlation coefficient greater than 0.8. Because the linearity assumption between average weight of the lot and sale price, determined by the statistical significance of the weight variable squared, was not

met, the variable was categorized. Four distinct weight group categories were defined based on common industry categorizations (less than 227 kg [<500 lb], 227–271 kg [500–599 lb], 272–317 kg [600–699 lb], and 318 kg or greater [≥ 700 lb]; Table 4.3). The sex variable included 3 levels, defined as “heifers” for lots including only heifer calves, “steers” for lots including only steer calves, and “mixed” for lots containing both steers and heifers (Table 4.3). It was suspected that there may be an interaction effect between sex and the VAP, therefore a 2-way interaction term between these 2 main effects was tested in the models. The U.S. geographic regions were designated as per the SLA system, which included 6 regional territories (Table 4.3). Regions 5 and 6 were collapsed for the purpose of this analysis due to sparsity of the data.

In both models, a first-order autoregressive covariance structure was fitted for month of sale to account for correlation of observations over time. A Tukey-Kramer adjustment of *P*-values for multiplicity was used for pairwise comparisons of fixed effects for the COMBO model only. This is because our objective for the COMBO model was to compare prices received for calf lots sold under the specific covariate pattern combinations of the COMBO model. Conversely, pairwise comparisons of fixed effects were not performed for the VAP model price estimates as the objective was not to compare significance between alternative marketing combinations, but rather was to compare and contrast VAP model estimates with COMBO model estimates, for each VAP combination. Model assumptions of homoscedasticity and normality were visually inspected using plots of standardized Pearson residuals.

Results and Discussion

Value-added programs

More than 40 different VAP are available when selling lots of cattle through the SLA services ([https:// superiorlivestock.com](https://superiorlivestock.com)). Value-added programs can be related to cattle sale

logistics, such as slide, 2-way slide, and weight stop; to nutritional management programs, including Gain Smart (BioZyme Inc., St. Joseph, MO), VitaFerm raised (BioZyme Inc., St. Joseph, MO), and Predictive Performance 90 (Riomax 360, Redwood Falls, MN); to vaccination and health related protocols (e.g., VAC24, VAC45, VAC60); and to genetic merit characteristics, such as Superior Progressive Genetics, Integrity Beef Genetic Merit, Top Dollar Angus, and others. In addition to these, there are other sets of verified programs related to a variety of management practices that are relevant to international treaty and domestic market demands that require third-party verification. Although there are many descriptors and VAP that can be designated for sale lots, these are not always clearly or consistently captured in datasets from cattle auctions. In the 2019 and 2020 datasets, BQA, GAP, and NHTC programs, as well as multiple vaccination and health related protocols (VAC24, VAC34(+), VAC45(+), VAC60) were reported by the consignor (or representative) in a designated VAP-specific data-entry field with a yes or no answer option. Therefore, we focused our research on these VAP that were consistent as in where and how they were reported in the dataset, and were reported frequently enough to have sufficient observations for analysis.

Study population

A total of 12,158 eligible calf lots sold through the SLA in 2019 and 2020 were identified and included in the final analysis. Observations not included in the final dataset were those that did not meet the specified inclusion criteria, outlined as follows: sale prices ranging from \$50/45.4 kg to \$300/45.4 kg (5,089 lots excluded), sex of the lots declared as weaned steer calves, steer calves, weaned heifer calves, heifer calves, or any combination of the sexes comprising mixed lots (9,362 excluded), lot weights ranging from 113 to 363 kg (85 excluded), lots of U.S. origin (30 excluded), lots containing some description of breed type (595 excluded),

lots with a breed type description that did not include Holstein or Holstein-cross (231 excluded), lots including any vaccination program, except VAC PRECON, or none (737 excluded), and lots that were home raised (685 excluded). No observations were excluded under the other stated exclusion criteria (i.e., lots of <5 animals or >5,000 animals, and breeding-type lots). Lots containing no entry in the selected VAP (VAC, BQA, NHTC, or GAP) were considered as having no claim (0). Therefore, the study population was composed of lots of home-raised, non-Holstein or Holstein-cross, steer and heifer calves, weighing between 113 and 363 kg on average, and of U.S. origin.

Frequency distributions of lots included in this analysis by weight category, sex, and U.S. region of sale are reported in Table 4.3. Weight categories were created based on 45.4 kg (100 lb) increments, where the majority (76%) of average calf lot weights in the present analysis ranged from 227 to 317 kg (500–699 lb). Approximately 42% of calf lots weighed over 272 kg (600 lb), where in contrast, the Livestock Marketing Information Center (LMIC, 2024) reported that 66% and 73% of national feeder and stocker cattle from video (internet) sales exceeded 272 kg (600 lb) in 2019 and 2020, respectively. This difference may in part be due to our focus on calf sales, whereas the data from the LMIC report, which uses the USDA–Agricultural Marketing Service (AMS) data, may not be calf-exclusive. Seeger et al. (2011) evaluated the effects of base weight and other factors on beef calf sale prices via SLA video auctions from 1995 to 2009, observing that sale prices decreased as the base weight of the lot increased, with the mean base weight of calf lots being ~245 kg (539 lb) from 1995 to 2002, and 255 kg (561 lb) from 2003 to 2009. From auction sales conducted between October 2021 and April 2022 across 7 U.S. states, Peel et al. (2024) similarly observed that feeder cattle prices decreased almost

linearly as mean lot weights increased, but with a small quadratic relationship resulting in moderation of this decline at heavier weights.

Approximately half of the total lots sold through the SLA in 2019 and 2020 were steers (51%), 31% were heifers, and 18% consisted of mixed-sex lots. The proportion of heifer receipts for 2019 and 2020 video (internet) sales of national feeder and stocker cattle were 40% and 36%, respectively (LMIC, 2024). The majority of the SLA calf lot sales in 2019 and 2020 originated from U.S. region 2 (Colorado, Montana, North Dakota, Nebraska, South Dakota, Utah, and Wyoming [41.23% of total lots]), followed by region 3 (Arkansas, Arizona, Louisiana, New Mexico, Oklahoma, and Texas [23.35%]), region 1 (California, Idaho, Nevada, Oregon, and Washington [17.72%]), and region 4 (Iowa, Illinois, Kansas, Minnesota, Missouri, and Wisconsin [7.21%]), with the remaining 10.49% of the total calf lots originating from regions 5 (Alabama, Florida, Georgia, and Mississippi), and 6 (all states northeast of and including Indiana, Kentucky, Michigan, North Carolina, South Carolina, and Tennessee). The estimated U.S. calf crop for 2019 and 2020 were 35,591,000 and 35,135,000, respectively (USDA, 2021). During each of the 2 years, ~11% of calves originated from the same states included in the SLA region 1, 22% were from states equivalent to region 2, 24% were from states comprised in region 3, 20% were from region 4 states, and 23% were from states of regions 5 and 6. Thus, our dataset of U.S. calf lots sold through the SLA market, was composed of a greater proportion of calves that originated from region 2 states, and a smaller proportion of calves originating from regions 4, 5, and 6 states, compared with the estimated national calf crop distribution in 2019 and 2020 (USDA, 2021).

Frequencies of VAP claims and market trends

Frequencies of VAP claims by calf lots sold through the SLA during 2019 and 2020 are reported in Table 4.1. McCabe et al. (2019a) evaluated the effects of breed composition on the sale prices of beef calves sold through video auctions and observed that Charolais- and Angus-sired calves received the highest premiums during the 2010 to 2016 timeframe. Although approximately half of the calf lots claimed Superior Progressive Genetics in our dataset, such VAP cannot be rapidly implemented into a producer's current calf inventory (i.e., this would require a long-run management change), and therefore genetic programs were not considered for our analyses. Some type of natural program was mentioned in ~43% of the calf lots; however, reporting of natural programs by the consignor was inconsistent. King et al. (2006), Burdine et al. (2014), and Odde et al. (2019) have previously reported on the effects of natural programs on calf lot sale prices and claiming trends. Burdine et al. (2014) reported a significant price premium of \$2.16/45.4 kg for natural feeder calves sold without implants, ionophores, or antibiotics through a large marketing firm in Kentucky, during the 2008 to mid-2011 timeframe. Although Odde et al. (2019) noted an upward trend in the percentage of lots claiming a natural program, increasing from 35% to 42% between 2010 to 2018, this percentage appeared to have plateaued at 43% in the subsequent years of 2019 and 2020. Other VAP included programs such as Integrated Management Information Global, Superior verified, Red Angus, Angus Source, and others. Approximately 36% of calf lots reported to be enrolled in at least one of the other VAP. Vaccination protocols, NHTC, BQA, and GAP are certification programs that could be incorporated into calf production system in the short-run, and these clearly defined programs were reported consistently. Approximately 87%, 28%, 15%, and 10% of the calf lots included in this analysis claimed some VAC program (with the majority enrolled in VAC34 and VAC45),

NHTC, BQA, and GAP respectively (Table 4.1). Less than 10% of the lots claimed the remaining VAP, including Bangs vaccine, other genetic merit programs, any of the nutritional programs, and cattle claimed as not persistently infected with bovine viral diarrhea virus.

After identification of the most relevant VAP and formation of COMBO levels, the frequencies for each COMBO were evaluated (Table 4.2). Lots that received VAC34 alone (VAC34-0-0-0), VAC45 alone (VAC45-0-0-0), or no VAP (0-0-0-0) were the most frequent in 2019 and 2020 SLA calf sales (27.82%, 14.99%, and 9.47% of total lots, respectively). Previous economic analysis performed by King et al. (2006), Seeger et al. (2011), and Zimmerman et al. (2012), all highlighted financial advantages associated with the adoption of VAC34 or VAC45 in calf lots compared with other VAC programs or no VAC. These early reports on price premiums associated with VAC programs likely promoted the most profitable options (i.e., VAC34 and VAC45), leading to their increased adoption in calf lots over time. Participation in the VAC45 program grew from 3.2% in 1995 to 26.8% in 2004, and VAC34 participation increased from 12.7% in 1995 to over 58% in 2005 (King et al., 2006). However, after these linear increases between 1995 and 2005, our combined dataset from 2019 and 2020 suggests a plateau in the growth of calf lots listed as VAC45 (28.43%), and a decrease in those listed as VAC34 (41.15%).

Value-added program combinations that were claimed by less than 1% of the total calf lots sold in 2019 and 2020 were collapsed into an “other” category, which mainly included lots claiming VAC60 and VAC24 combinations (except VAC60-0-0-0, VAC60-NHTC-0-0, and VAC24-0-0-0), BQA-only lots (0-0-BQA-0), GAP-only lots (0-0-0-GAP), and no vaccine with other VAP lots (0-NHTC-0-BQA, 0-NHTC-0-GAP, 0-NHTC-BQA-0, 0-NHTC-BQA-GAP). Approximately 6% of the total number of lots were collapsed into “other.” Previous analyses,

which did not include the newer VAC60 program, found that calves with the VAC24 claim received significantly lower premiums compared with other verified health claims, and these premiums were not statistically different from those paid for calves with noncertified single vaccination record (Zimmerman, 2010). The lack of financial justification for implementing VAC24, as indicated by the aforementioned studies, and the absence of evidence supporting economic advantage associated with VAC60 (as it was not considered or did not exist at the time of previous analyses), may explain the infrequent inclusion of these VAC programs in calf lot VAP profiles.

VAP combinations and calf lot sale price

Statistical significance of the association between variables and calf lot sale price for the COMBO and VAP models are reported in Table 4.4. In the COMBO model, COMBO was significantly associated with calf lot sale price ($P < 0.01$); however, its association depended on sex (as per a significant COMBO $\times$ sex interaction, $P < 0.01$). Weight category and U.S. region of calf lots were significantly associated with sale price in both COMBO and VAP models ($P < 0.01$; Table 4.4). The interaction between COMBO and weight categories was not evaluated due to a lack of practical justification. Further stratifying price estimates by COMBO, sex, and weight category would have complicated the interpretation and reduced its relevance to real-life scenarios with practical meaning to the producer. Specifically, price estimates per COMBO category may have needed to be stratified not only by sex, as is currently presented, but also by weight categories within each sex. Similarly, interactions between COMBO and U.S. region of sale were not evaluated. This analytical consideration aligns with previous research (Troxel and Gadberry, 2013; Williams et al., 2014), which evaluated calf characteristics as independent variables for sale price estimates. These studies reported the highest prices for steer lots,

followed by bulls, heifers, and mixed lots, also without accounting for potential sex $\times$ weight interactions. Conversely, sex $\times$ weight interactions for bulls and heifers have been noted by Parish et al. (2018).

When testing the effects of individual VAP on calf lot sale prices (VAP model; Table 4.4), VAC programs and NHTC status were significantly associated with sale price, but effects were modified by sex of the lot (VAC $\times$ sex, $P < 0.01$; NHTC $\times$ sex, $P = 0.01$). Global Animal Partnership certification significantly affected calf lot sale price, independent of sex (GAP, $P < 0.01$; GAP $\times$ sex, $P = 0.27$). Beef Quality Assurance certification alone was not significantly associated with calf lot sale price ($P = 0.97$); however, there was marginal significance for an association with price, depending on the sex of the lot (BQA $\times$ sex, $P = 0.06$). Although there was not a significant interaction for GAP $\times$ sex, and only a marginally significant interaction for BQA $\times$ sex, the respective interactions were still retained in the final VAP model, as this was necessary for comparison with the COMBO model.

Sale prices associated with VAP combinations (estimated via both COMBO and VAP models) for an average lot weight and U.S. region (i.e., averaged across weight and region effects), are presented for steers (Table 4.5), heifers (Table 4.6), and mixed lots (Table 4.7). For steer lots (Table 4.5), VAC45-NHTC-BQA-GAP and VAC45-NHTC-0-GAP were associated with the highest sale prices (\$172.71 and \$171.81/45.4 kg, respectively; i.e., the inclusion or exclusion of BQA did not result in a significantly different price between these 2 COMBO levels). In contrast, VAC24-0-0-0, VAC34-0-0-0, and VAC34-0-BQA-0 were the VAP combinations that received the lowest prices when marketing steer-calf lots (\$151.05, \$154.27, and \$155.28/45.4 kg, respectively). Lots without any VAP claim (0-0-0-0) not only received significantly greater sale prices (\$156.32/45.4 kg) compared with those only claiming VAC24-0-

0-0 or VAC34-0-0-0, but were also valued similarly to all other COMBO levels, except: 2 aforementioned highest valued combinations, VAC45-NHTC-BQA-0 (\$166.48/45.4 kg), VAC45-NHTC-0-0 (\$164.61/45.4 kg), and other (\$163.66/45.4 kg).

Similar to steers, heifer lots claiming VAC45-NHTC-BQA-GAP and VAC45-NHTC-0-GAP also achieved the highest sale prices (Table 4.6). Heifer lots with no VAP claims (0-0-0-0) were valued significantly greater (\$140.69/45.4 kg) in the calf market compared with those claiming VAC24-0-0-0 (\$135.38/45.4 kg). Other VAC combinations with no NHTC, NHTC with no VAC, and VAC34-NHTC-BQA-0 were not valued any more than those having no VAP claim.

When marketing mixed-sex calf lots (Table 4.7), the highest sale prices were associated with VAC45-NHTC-0-GAP (\$156.10/45.4 kg), VAC45-NHTC-BQA-GAP (\$155.52/45.4 kg), and VAC45-NHTC-0-0 (\$152.81/45.4 kg) COMBO claims. Contrarily to steers and heifers, only the first 7 COMBO levels listed in Table 4.7, plus other received significantly greater sale prices than mixed lots claiming no VAP (0-0-0-0; \$145.00/45.4 kg).

For steer, heifers and mixed lots, the first contrast between COMBO and VAP model estimates can be made when considering BQA claims. Based on the VAP model, the effect of BQA claim was marginally significant on calf lot sale price, yielding approximate average premiums of +\$1.66/45.4 kg in steer, +\$0.66/45.4 kg in heifer, and -\$1.07/45.4 kg in mixed lots. In the COMBO model, the average price difference from adding BQA claim to the corresponding VAP profile lot ranged from -\$0.14 to +\$1.87/ 45.4 kg in steer lots, -\$1.32 to +\$0.92/ 45.4 kg in heifer lots, and -\$3.41 to -\$0.57/45.4 kg in mixed lots, depending on the specific VAP combination. These observations underscore the contextual importance of other VAP claims in determining calf lot sale prices.

Seeger et al. (2011) analyzed 15 years (1995–2009) of calf lot sale prices via the SLA using a multivariable regression model assuming all VAP to be independent of one another, and found that sale prices were significantly greater for VAC34 and VAC45 lots compared with similar calves that were not in a certified health program, not vaccinated against respiratory viruses, and not weaned before shipment. Conclusions from Seeger et al. (2011) are in line with others who have similarly evaluated the effects of certified vaccination programs on calf lots sale prices during overlapping, shorter timeframes (King et al., 2006; Zimmerman, 2010). King et al. (2006) reported 10-year premiums (between 1995 and 2005) associated with VAC45 calves, which ranged from \$2.47 to \$7.91/45.4 kg, whereas VAC34 calf lots ranged from \$0.99 to \$3.47/45.4 kg, depending on the year, compared with calves that were not vaccinated. Seeger et al. (2011), extending the timeframe by 5 years, reported greater maximum premiums: \$2.47 to \$8.20/45.4 kg for VAC45, and \$0.99 to \$4.68/45.4 kg for VAC34. Similarly, Zimmerman (2010) reported VAC45 premiums of \$7.61/45.4 kg for steers and \$6.61/45.4 kg for heifers from 2008 to 2009, whereas VAC24 received the lowest premiums among certified VAC alternatives, and was similar in value to non-VAC certified lots. In 2019 and 2020, VAC24 inclusion in lots otherwise claiming no VAP resulted in discounted sale prices in both models (–\$1.07 to –\$5.30/45.4 kg), regardless of sex. Early studies evaluating effects of VAC claims on calf sale prices did not account for the newer VAC60 program (King et al., 2006; Zimmerman, 2010; Seeger et al., 2011). More recent work (Williams et al., 2023) looked at a different arrangement of health management practices and reported vaccination to be associated with the highest individual premiums (\$6.79/45.4 kg) compared with weaning and dehorning (both yielding premiums of ~\$5.25/45.4 kg). When combining weaned, vaccinated, dehorned, and certified (i.e., VAC45) the reported average premium was \$12.46/45.4 kg, with a probability of positive

net return of 78.7%. In our analysis of 2019 to 2020 sales, VAC45 premiums in steer lots were \$3.13/45.4 kg based on the VAP model and ranged from \$2.32 to \$3.12/45.4 kg based on the COMBO model. For heifer lots, the VAP model estimate was \$2.89/45.4 kg for VAC45, whereas COMBO model estimates ranged from \$1.55 to \$7.16/45.4 kg. For mixed lots, COMBO model estimates for VAC45 ranged from \$2.41 to \$9.18/45.4 kg, compared with an average premium of \$3.07/45.4 kg in the VAP model.

Although NHTC certification was associated with a premium during 2008 (the year of program introduction), no impacts on sale prices were observed in the following year (Zimmerman, 2010; Seeger et al., 2011). Subsequently, McCabe et al. (2019b) analyzed sale prices associated with NHTC status using a 9-year dataset (2010–2018) of beef calves sold through the SLA market. They observed that NHTC-certified cattle earned significantly greater premiums compared with their non-NHTC counterparts in most years (except in 2015 and 2016), with premiums ranging from \$2.28 to \$4.04/45.4 kg. Furthermore, earlier studies evaluating premiums associated with NHTC status in calves either failed to report or did not consider the effect of other VAP on the association between NHTC status and sale price. Our analysis of more recent data, which accounts for alternative factors (e.g., other VAP), supports a more nuanced conclusion. In our 2019 and 2020 COMBO analysis, addition of a NHTC claim to steer lots yielded premiums ranging from \$4.03 to \$5.97/45.4 kg when claimed alone or in combination with VAC45, VAC 34, or VAC60, whereas the VAP model estimated an average premium of \$5.24/45.4 kg for any steer lot claiming NHTC. Sale prices for steer lots claiming NHTC without VAC45, whether combined with BQA or GAP, were statistically similar to those associated with lots claiming no VAP. For heifers, NHTC premiums ranged from \$0.62 to \$9.03/45.4 kg, depending on the combination of other VAP claims, while the VAP model

estimated a premium of \$5.03/45.4 kg for the addition of NHTC to any heifer lot. In mixed lots, the COMBO model estimated premiums ranging from −\$1.37 to 6.31/45.4 kg when adding NHTC, whereas the VAP model estimated an average of \$2.77/45.4 kg premium for any mixed lot that adds NHTC.

Zimmerman (2010) and Seeger et al. (2011) had limited data points in their datasets due to the timeframe of their studies on the effects of NHTC certification on calf sale prices. This limitation restricted their ability to draw definitive conclusions about NHTC premiums, given that NHTC certification began in 2008. Since 2016 the USDA-AMS began reporting weighted average (range) premiums for harvested NHTC cattle on a carcass basis, and since then (until 2024), the reported premiums yielded for fed cattle ranged from ~\$17 to \$23/45.4 kg on average (LMIC, 2024). Although calf purchases do not necessarily have a defined premium associated with NHTC certification, producers presumably purchase NHTC calves with the intent of them remaining in that program, with the expectation of receiving a premium when finished. Based on the 2019 and 2020 COMBO analysis, this premium incentive at the end of the production phase of fed cattle seems to be at least partially transferred to the calf producer, with NHTC calf lots receiving greater average prices than their traditional counterparts. For example, in heifer lots, a \$9.03/45.4 kg premium was observed when adding NHTC to VAC60 (i.e., VAC60-NHTC-0-0 vs. VAC60-0-0-0; $P < 0.05$); in steer lots, a \$5.97/45.4 kg premium was associated with the additional claim of NHTC to VAC45 (VAC45-NHTC-0-0 vs. VAC45-0-0-0; $P < 0.05$); and in mixed lots, a significant difference of \$3.92/45.4 kg was observed between VAC34-NHTC-0-0 and VAC34-0-0-0.

The BQA program was established in 1987 with the objective of improving animal health, welfare, safety, and quality of beef products, while also promoting consumer confidence

in the beef industry. When Mooney et al. (2019) investigated the effect of mentioning BQA in video auction lot descriptions on the sale price of beef calves and feeder cattle lots, they found that ~2.6% of the total lots sold through the Western Video Market from 1997 to 2017 included a BQA mention. These lots received an average premium of \$1.14/45.4 kg across all years considered, and \$2.69/45.4 kg when considering only from 2010 to 2017 (Mooney et al., 2019). However, based on the alternative COMBO model analysis used here, the inclusion of BQA in lots claiming a VAC program, NHTC, and GAP, did not result in greater sale prices, independent of the sex of the lot. However, it is possible that the BQA claims were underreported for lots that had other VAP claims. The BQA certification is not typically free, but the cost can vary depending on the state and the type of certification (online or in-person). Furthermore, although financial benefits of the BQA claim may be marginally dependent on the sex of the lot, a survey conducted by Klopatek et al. (2022) revealed that the primary motivation for ranchers to become BQA certified were (1) “consumer perceptions/demands/concerns about animal welfare,” and (2) “reputation of their operation is greater when animals are a part of BQA,” with only 22% of ranchers reporting the greater sale value for BQA animals as one of their top reasons for becoming BQA certified.

In alignment with BQA standard practices and goals, GAP certification also aims to enhance consumer confidence in the animal production system by promoting improvement of farm animal welfare through the development, application, and verification of multilevel practice standards across the supply chain. The GAP certification requires a base fee of \$100, with additional variable costs, depending on the operation, the number of farms to be audited, and the auditor’s travel expenses. Few studies have examined the impact of GAP certification on sale prices of calf lots. According to the COMBO analysis, the premium associated with adding GAP

to lots already enrolled in a VAC program and NHTC varied depending on the sex. For steer and heifer lots, incorporating GAP into the VAC45 and NHTC combination (VAC45-NHTC-0-GAP) resulted in an additional premium of \$7.20/45.4 kg compared with the counterpart combination without GAP (i.e., VAC45-NHTC-0-0; $P < 0.05$). However, in mixed-sex lots, the premium difference between those 2 COMBO was not significant. Furthermore, for lots enrolled in VAC programs other than VAC45, the addition of GAP did not yield a significant premium, regardless of the sex of the lot.

It is important to recognize that COMBO lots with more VAP, priced similarly to those claiming fewer VAP, would presumably have a greater initial investment (cost). As a result, the net return for lots including fewer VAP would likely be greater than for those with more VAP, when sold for similar prices. Williams et al. (2023) reported results from a similar analysis exercise examining the independent and combined effects of weaning, vaccinating, dehorning, and certification in preconditioning programs on calf sale prices. Their findings indicated that calves that were only weaned (+\$5.23/45.4 kg) or only vaccinated (+\$6.79/45.4 kg) had a greater average price effect than those that were both weaned and vaccinated (+\$4.86/45.4 kg). Ultimately, when evaluating the premiums associated with different combinations of management practices and determining the best option for an operation, producers should carefully consider the unique costs associated with certification and the underlying motivation, whether it is primarily driven by economics or by social considerations.

When comparing sale price estimates between the COMBO and VAP model, the combination of VAC45, NHTC, and GAP, with or without BQA, yielded the highest sale prices compared with all other VAP combinations, according to both model estimations, for all sexes. On the opposite end of the spectrum, VAC24-0-0-0, VAC34-0-0-0, and VAC34-0-BQA-0,

yielded the lowest numerical mean sale price for all sexes, according to both models; based on pairwise comparisons from the COMBO model, these sale values were either similar or significantly lower than those obtained by lots claiming no VAP (0-0-0-0), depending on sex.

In the COMBO model, a lot sold as VAC45, NHTC, no BQA, and GAP has a single explanatory variable for the specified combination of VAP, where the model adjusted value directly estimates prices received for calves actually sold under that combination of VAP. Alternatively, the VAP model estimates a different coefficient for each subcategory within each VAP; so, if one wanted to estimate the value of a lot sold under the same combination of VAP specified above, we would be assuming that the additive linear combination of the VAP model coefficients are equivalent to the COMBO model estimate. This may or may not be reasonable, as there is potential for diminishing returns as more VAP are incorporated into a lot of calves. Value-added programs may not have mutually independent effects on sale prices; there may be different combinations of VAP that are more frequently associated together.

Although both modeling strategies arrived at similar conclusions regarding which VAP combinations in sex-specific calf lots received the highest and lowest prices, mean prices varied depending on the strategy. The marginal difference between the modeled prices ranged from small to potentially meaningful, depending on the specific VAP combination and sex of the lot. For steers, the largest difference was for VAC34-NHTC-0-GAP lots, where estimated mean sale prices were \$162.55/45.4 kg based on the COMBO model, and \$165.15/45.4 kg based on the VAP model, a \$2.60/45.4 kg difference (or 1.57% relative difference) between the 2 models. There were 2 additional cases for steer lots where the marginal difference between models exceeded \$1.00/45.4 kg, which were VAC45-NHTC-0-GAP and VAC34-NHTC-BQA-0. For heifer lots, estimated mean sale prices differences between the 2 models was greater than

\$3.50/45.4 kg in some cases (i.e., 0-NHTC-0-0 and VAC34-NHTC-0-GAP). The reader may need to determine what they would consider an economically significant difference between the 2 approaches, and how precise the desired estimate needs to be.

When combining frequent VAP in a single COMBO variable, infrequent combinations were combined into an “other” category with no applicable meaning to the producer (i.e., sale prices for infrequent combinations were not estimated), which highlights a disadvantage of the COMBO model approach compared with the VAP model. In the VAP model, all VAP combinations, including infrequent ones, can be estimated; however, the precision of sale prices estimated for infrequent combinations may decline. The price associated with each VAP is estimated by averaging the sale prices of all lots claiming the specific VAP program (within sex), while controlling for other VAP, weight, and U.S. region. The estimated premiums associated with each VAP are then added to the average price for no VAP claims (the intercept) to estimate the sale price of a lot with a specific VAP combination. This approach assumes that VAP programs are independent of one another when estimating their effects on sale price. Although this assumption of independence is made for simplification and practicality of the model, we speculated that a calf lot claiming all VAP may not sell for the value estimated by the VAP model (i.e., sum of all premiums associated with each VAP independently, on top of the base price [average price of lots with no VAP]). The alternative COMBO model was hypothesized to produce more realistic estimates of prices, where VAP are not considered independent, and concerns of multicollinearity among VAP (if any) are removed. However, there was no multicollinearity among the independent explanatory variables in either model. Ultimately, when considering the 4 specific VAP combinations analyzed (VAC, NHTC, BQA, and GAP), our findings indicated that both models provide similar interpretations that would likely not differ

meaningfully to producers in most cases. The impact of considering additional programs, or different VAP was beyond the scope of this analysis, and these results should not be extrapolated to scenarios outside the specifics of this research.

Limitations and future research

There are limitations of this research to consider. The analysis was derived from a large and robust observational dataset, thereby leading to appreciable external validity. However, all data originated from lots sold through SLA video auctions, and the degree in which the findings can be extrapolated to calves sold through other market channels is largely unknown. Other variables available in the dataset, such as frame, flesh, breed, and the presence of horns, which could affect sale price estimates, were not included in the model. These variables were not considered due to the complexity and inconsistency in how they were recorded and reported by consignors or cattle owners. For example, entries for breed types such as, “Out of English cross & Brahman cross cows by Brangus, Angus & Charolais bulls, carrying 3/8 or less Brahman influence,” would be challenging to standardize into distinct categories.

Nominal (not adjusted for inflation) cattle prices have markedly increased since the timeframe of calf sales in the source data and the time of publication. It is unknown how these price changes may impact the findings; however, changing baseline prices may not affect the marginal differences or effects of VAP. In other words, the relative change in calf price that occurs when incorporating a given VAP may still apply to recent, greater calf prices; greater prices do not necessarily mean VAP effects and market preferences toward certain VAP combinations are altered. Assuming relative differences remain constant, our model results could be interpreted for different prices on percent difference basis (e.g., \$148.50/45.4 kg to \$150.00/45.4 kg as a 1.0% relative increase). Still, future research with updated data on calf sales

is needed for confirmation of price premiums and market preferences over time. Additionally, more consistent and reliable recording of other potential covariates could yield more robust analyses.

Applications

The impact of VAP combinations on sale price varied depending on the sex of the lot, and although both models reached similar overall conclusions when treating VAP as independent (VAP model) or interdependent (COMBO model), they differed in their estimation capabilities, particularly for infrequent VAP combinations. Nevertheless, both models yielded broadly consistent insights, indicating that VAP such as VAC45 combined with NHTC and GAP can command meaningful price premiums in steer, heifer, and mixed lots. Specific VAP combinations are better incentivized by the marketplace than others, and implementation of those specific combinations may be an effective means for adding value to calf lots. However, producers should carefully match VAP choices to their operational goals. It is important for producers to account for the production costs associated with each VAP, as these costs were not considered in this analysis. When selecting a VAP to be implemented in a calf lot, producers should consider whether expected premiums outweigh any additional costs. By understanding the marginal impacts of different VAP combinations, producers may be able to make more informed decisions, optimizing their management and marketing strategies to maximize profitability of their calf crop. Overall, these analyses support the objective of estimating prices for practical, short-run VAP decisions, providing producers and feeders with clear information, as they strive for calf lot value optimization in the marketplace.

Funding

This research was supported by Merck Animal Health (De Soto, KS), and the Center of Outcomes Research and Epidemiology at the College of Veterinary Medicine, Kansas State University (Manhattan, KS). Contribution no. 25-022-J from the Kansas Agricultural Experiment Station (Manhattan, KS).

Acknowledgments

The authors express their gratitude to Superior Livestock Auction for their collaboration in providing the dataset for this research.

Conflict of Interest

One of the authors works for Merck Animal Health (De Soto, KS), and 5 of the authors work for the Center of Outcomes Research and Epidemiology at the College of Veterinary Medicine, Kansas State University, which provided funding. The authors declare that they have no commercial or financial relationships that could be perceived as potential conflicts of interest related to this research.

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Tables and Figures

Table 4.1. Frequency statistics of value-added programs claims for calf lots sold through the Superior Livestock Auction (SLA) from January 2019 through December 2020

SLA value-added programs^{1,2}	No. of lots	Percent of total
Any SLA VAC program	10,616	87.32
VAC24	989	8.13
VAC34	3,305	27.18
VAC34+	1,699	13.97
VAC45	2,942	24.20
VAC45+	514	4.23
VAC60	1,167	9.60
Superior Progressive Genetics	5,659	46.55
Any natural program	5,239	43.09
Natural Plus	2,271	18.68
Natural	600	4.94
Verified Natural	2,368	19.48
Other value-added Superior programs	4,381	36.03
Superior	2,821	23.20
Red Angus	579	4.76
Other	487	4.01
IMI Global	318	2.62
Angus Source	102	0.84
Sterling	74	0.61
Non-hormone treated cattle (NHTC)	3,393	27.91
Beef Quality Assurance (BQA)	1,847	15.19
Global Animal Partnership (GAP)	1,151	9.47
Bangs vaccine	905	7.44
Any genetic merit program ³	277	2.28
Any nutrition program ⁴	151	1.24
PI free	139	1.14

¹ Description and requirement associated with each of the SLA value-added programs can be found at:

<https://superiorlivestock.com/value-added-programs/>.

² VAC = vaccination program; IMI = Integrated Management Information Global; PI Free = cattle not persistently infected with bovine diarrhea virus.

³ Includes Superior Progressive Genetics, Integrity Beef Genetic Merit, and Top Dollar Angus.

⁴ Includes VitaFerm (BioZyme Incorporated, St. Joseph, MO), Gain Smart (BioZyme Incorporated, St. Joseph, MO), and Verified Grass Fed.

Table 4.2. Frequency statistics of claimed combinations of value-added programs (VAC, NHTC, BQA, and GAP) for calf lots sold through the Superior Livestock Auction from January 2019 through December 2020

Program combination (VAC-NHTC-BQA-GAP)¹	No. of lots	Percent of total
VAC34-0-0-0	3,382	27.82
VAC45-0-0-0	1,822	14.99
0-0-0-0	1,151	9.47
VAC24-0-0-0	813	6.69
VAC60-0-0-0	669	5.50
VAC45-NHTC-0-0	647	5.32
VAC34-NHTC-0-0	485	3.99
VAC34-0-BQA-0	450	3.70
VAC34-NHTC-0-GAP	328	2.70
VAC45-NHTC-0-GAP	303	2.49
VAC45-0-BQA-0	279	2.29
VAC34-NHTC-BQA-0	260	2.14
VAC45-NHTC-BQA-0	249	2.05
VAC60-NHTC-0-0	236	1.94
0-NHTC-0-0	226	1.86
VAC45-NHTC-BQA-GAP	153	1.26
VAC60-NHTC-0-GAP ²	111	0.91
VAC34-NHTC-BQA-GAP ²	94	0.77
0-0-BQA-0 ²	81	0.67
VAC24-0-BQA-0 ²	59	0.49
VAC60-NHTC-BQA-GAP ²	54	0.44
VAC60-NHTC-BQA-0 ²	52	0.43
0-NHTC-0-GAP ²	44	0.36
VAC60-0-BQA-0 ²	44	0.36
VAC24-NHTC-0-0 ²	42	0.35
VAC24-NHTC-0-GAP ²	37	0.30
VAC24-NHTC-BQA-0 ²	37	0.30
0-NHTC-BQA-0 ²	23	0.19
0-NHTC-BQA-GAP ²	11	0.09
0-0-0-GAP ²	6	0.05
VAC34-0-0-GAP ²	5	0.04
VAC45-0-0-GAP ²	3	0.02
VAC24-NHTC-BQA-GAP ²	1	0.01
VAC60-0-0-GAP ²	1	0.01

¹ Zero (“0”) means no claim; VAC means vaccination program (VAC34 and VAC34+ were combined into a single group “VAC34”, and VAC45 and VAC45+ were combined into “VAC45”); NHTC means non-hormone treated cattle; BQA means Beef Quality Assurance cattle; GAP means Global Animal Partnership cattle.

²Collapsed into “other” category for the COMBO-model analysis.

Table 4.3. Frequency statistics of calf lots sold through the Superior Livestock Auction network from January (2019) through December (2020) by weight category, sex, and U.S. region

Covariate	No. of lots	Percent of total
Weight category of the lot		
< 227 kg (< 500 lb)	1,852	15.23
227-271 kg (500-599 lb)	5,168	42.51
272-317 kg (600-699 lb)	4,073	33.50
≥ 318 kg (≥ 700 lb)	1,065	8.76
Sex of the lot		
Steer	6,176	50.80
Heifer	3,802	31.27
Mixed	2,180	17.93
SLA U.S. Region¹		
Region 1	2,154	17.72
Region 2	5,013	41.23
Region 3	2,839	23.35
Region 4	877	7.21
Regions 5 & 6	1,275	10.49

¹ Six United States (U.S.) regions were defined: 1 (CA, ID, NV, OR, and WA), 2 (CO, MT, ND, NE, SD, UT, and WY), 3 (AR, AZ, LA, NM, OK, and TX), 4 (IA, IL, KS, MN, MO, and WI), 5 (AL, FL, GA, and MS), and 6 (all states Northeast of, and including IN, KY, MI, NC, SC, and TN). Due to low transaction volume and multi-collinearity concerns, regions 5 and 6 were combined for the analysis.

Table 4.4. Statistical significance testing of fixed effects for the COMBO- and VAP- (value-added programs) models, both estimating sale prices associated with calf lots sold through the Superior Livestock Auction network from January (2019) through December (2020)

Variable¹	<i>P</i>-value
COMBO model	
Value-added programs combination (COMBO)	< 0.01
Weight category of the lot	< 0.01
SLA U.S. Region	< 0.01
Sex of the lot	< 0.01
COMBO × sex	< 0.01
VAP model	
VAC program	< 0.01
BQA program	0.97
NHTC program	< 0.01
GAP program	< 0.01
Weight category of the lot	< 0.01
SLA U.S. Region	< 0.01
Sex of the lot	< 0.01
VAC program × sex	< 0.01
BQA × sex	0.06
GAP × sex	0.27
NHTC × sex	0.01

¹ VAC means vaccination program; NHTC means non-hormone treated cattle; BQA means Beef Quality Assurance cattle; GAP means Global Animal Partnership cattle; SLA = Superior Livestock Auction; U.S. = United States of America.

Table 4.5. Mean sale prices and standard errors of the means (SEM) per VAC-NHTC-BQA-GAP program combination for steer lots sold through the Superior Livestock Auction network from January (2019) through December (2020), controlling for weight category of the lot, U.S. region, and month of sale

Value-added programs combination ^{1,2}	COMBO model estimates		VAP model estimates		Estimate difference ⁴
	Mean price ³ , \$/45 kg	SEM	Mean price, \$/45 kg	SEM	
VAC45-NHTC-BQA-GAP	172.71 ^a	0.997	172.27	0.491	0.44
VAC45-NHTC-0-GAP	171.81 ^a	0.728	170.62	0.442	1.19
VAC45-NHTC-BQA-0	166.48 ^b	0.790	166.06	0.418	0.42
VAC45-NHTC-0-0	164.61 ^c	0.516	164.40	0.362	0.21
Other	163.66 ^{d, c}	0.482	-	-	-
VAC34-NHTC-0-GAP	162.55 ^{d, e}	0.694	165.15	0.449	-2.60
VAC60-NHTC-0-0	162.09 ^{d, e}	0.822	162.95	0.473	-0.86
0-NHTC-0-0	161.49 ^e	0.802	161.27	0.447	0.22
VAC45-0-BQA-0	160.78 ^e	0.747	160.82	0.394	-0.04
VAC34-NHTC-0-0	159.45 ^e	0.588	158.93	0.373	0.52
VAC34-NHTC-BQA-0	159.31 ^e	0.772	160.59	0.436	-1.28
VAC45-0-0-0	158.64 ^e	0.352	159.16	0.302	-0.52
VAC60-0-0-0	157.04 ^e	0.536	157.71	0.436	-0.67
0-0-0-0	156.32 ^{e, f}	0.430	156.04	0.379	0.28
VAC34-0-BQA-0	155.28 ^{f, h}	0.628	155.35	0.390	-0.07
VAC34-0-0-0	154.27 ^h	0.311	153.69	0.285	0.58
VAC24-0-0-0	151.05 ^h	0.528	151.43	0.475	-0.38

¹ Zero (“0”) means no claim; VAC means vaccination program (VAC34 and VAC34+ were combined into a single group “VAC34”, and VAC45 and VAC45+ were combined into “VAC45”); NHTC means non-hormone treated cattle; BQA means Beef Quality Assurance cattle; GAP means Global Animal Partnership cattle; U.S. = United States of America.

² COMBO × Sex interaction $P < 0.01$.

³ Mean prices with different superscript letters within COMBO price column are significantly different after adjustment for multiple comparisons ($P < 0.05$). A Tukey-Kramer adjustment for multiplicity was used for pairwise comparisons of fixed effects for the COMBO-model only, and not for the VAP-model price estimates as the objective was to only contrast the VAP-model and COMBO-model estimates, for each VAP combination.

⁴ Differences between COMBO- and VAP-model estimates (VAP-estimate subtracted from COMBO-estimate).

Table 4.6. Mean sale prices and standard errors of the means (SEM) per VAC-NHTC-BQA-GAP program combination for heifer lots sold through the Superior Livestock Auction network from January (2019) through December (2020), controlling for weight category of the lot, U.S. region, and month of sale

Value-added program combination ^{1,2}	COMBO model estimates		VAP model estimates		Estimate difference ⁴
	Mean price ³ , \$/45 kg	SEM	Mean price, \$/45 kg	SEM	
VAC45-NHTC-0-GAP	155.70 ^a	0.857	153.89	0.516	1.81
VAC45-NHTC-BQA-GAP	154.38 ^{a, b}	1.199	154.54	0.585	-0.16
VAC60-NHTC-0-0	150.03 ^{b, c}	0.932	148.27	0.544	1.76
Other	148.69 ^{b, c, d, e}	0.590	-	-	-
VAC45-NHTC-0-0	148.47 ^{b, c, d, e}	0.618	147.71	0.425	0.76
VAC45-NHTC-BQA-0	147.50 ^{c, d, e, f}	0.956	148.37	0.499	-0.87
VAC34-NHTC-0-GAP	145.89 ^{d, e, f}	0.834	149.46	0.524	-3.57
VAC34-NHTC-0-0	143.66 ^{e, f, g, h}	0.742	143.28	0.441	0.38
VAC45-0-BQA-0	143.16 ^{f, g, h, i}	0.914	143.34	0.477	-0.18
VAC34-NHTC-BQA-0	142.46 ^{g, h, i}	0.999	143.94	0.522	-1.48
VAC45-0-0-0	142.24 ^{h, i}	0.408	142.68	0.346	-0.44
0-NHTC-0-0	141.31 ^{h, i, j}	0.977	144.81	0.532	-3.50
VAC60-0-0-0	141.00 ^{i, j}	0.606	143.24	0.487	-2.24
0-0-0-0	140.69 ^{i, j}	0.505	139.79	0.445	0.90
VAC34-0-0-0	139.04 ^j	0.364	138.26	0.325	0.78
VAC34-0-BQA-0	139.00 ^j	0.805	138.92	0.472	0.08
VAC24-0-0-0	135.38 ^k	0.658	135.15	0.589	0.23

¹ Zero (“0”) means no claim; VAC means vaccination program (VAC34 and VAC34+ were combined into a single group “VAC34”, and VAC45 and VAC45+ were combined into “VAC45”); NHTC means non-hormone treated cattle; BQA means Beef Quality Assurance cattle; GAP means Global Animal Partnership cattle; U.S. = United States of America.

² COMBO × Sex interaction $P < 0.01$.

³ Mean prices with different superscript letters within COMBO price column are significantly different after adjustment for multiple comparisons ($P < 0.05$). A Tukey-Kramer adjustment for multiplicity was used for pairwise comparisons of fixed effects for the COMBO-model only, and not for the VAP-model price estimates as the objective was to only contrast the VAP-model and COMBO-model estimates, for each VAP combination.

⁴ Differences between COMBO- and VAP-model estimates (VAP-estimate subtracted from COMBO-estimate).

Table 4.7. Mean sale prices and standard errors of the means (SEM) per VAC-NHTC-BQA-GAP program combination for mixed lots sold through the Superior Livestock Auction network from January (2019) through December (2020), controlling for weight category of the lot, U.S. region, and month of sale

Value-added program combination ^{1,2}	COMBO model estimates		VAP model estimates		Estimate difference ⁴
	Mean price ³ , \$/45 kg	SEM	Mean price, \$/45 kg	SEM	
VAC45-NHTC-0-GAP	156.10 ^a	1.833	154.73	1.073	1.37
VAC45-NHTC-BQA-GAP	155.52 ^{a, b}	3.762	153.66	1.190	1.86
VAC45-NHTC-0-0	152.81 ^{a, b}	1.258	150.62	0.754	2.19
VAC60-NHTC-0-0	150.23 ^{b, c}	1.595	152.65	0.854	-2.42
VAC34-NHTC-0-0	150.08 ^{b, c}	1.441	148.55	0.742	1.53
VAC60-0-0-0	149.86 ^{b, c}	0.723	149.88	0.650	-0.02
VAC34-NHTC-BQA-0	149.51 ^{b, c, d}	2.055	147.48	0.914	2.03
Other	149.47 ^{b, c, d}	1.048	-	-	-
VAC45-NHTC-BQA-0	149.40 ^{b, c, d, e}	2.802	149.55	0.935	-0.12
VAC34-NHTC-0-GAP	148.07 ^{b, c, d, e, f}	2.506	152.66	1.079	-4.59
VAC45-0-0-0	147.41 ^{c, d, e, f}	0.493	147.85	0.451	-0.44
VAC45-0-BQA-0	146.54 ^{c, d, e, f}	1.602	146.78	0.810	-0.24
VAC34-0-0-0	146.16 ^{d, e, f}	0.375	145.78	0.360	0.38
0-0-0-0	145.00 ^{e, f}	0.526	144.78	0.495	0.22
VAC24-0-0-0	143.83 ^{e, f, g}	0.575	143.71	0.554	0.12
0-NHTC-0-0	143.63 ^{e, f, g, h, i}	1.854	147.55	0.804	-3.92
VAC34-0-BQA-0	143.20 ^{f, g, h, i}	1.157	144.71	0.750	-1.51

¹ Zero (“0”) means no claim; VAC means vaccination program (VAC34 and VAC34+ were combined into a single group “VAC34”, and VAC45 and VAC45+ were combined into “VAC45”); NHTC means non-hormone treated cattle; BQA means Beef Quality Assurance cattle; GAP means Global Animal Partnership cattle; U.S. = United States of America.

² COMBO × Sex interaction $P < 0.01$.

³ Mean prices with different superscript letters within COMBO price column are significantly different after adjustment for multiple comparisons ($P < 0.05$). A Tukey-Kramer adjustment for multiplicity was used for pairwise comparisons of fixed effects for the COMBO-model only, and not for the VAP-model price estimates as the objective was to only contrast the VAP-model and COMBO-model estimates, for each VAP combination.

⁴ Differences between COMBO- and VAP-model estimates (VAP-estimate subtracted from COMBO-estimate).

Chapter 5 - Conclusions

Across the projects presented in the different chapters of this dissertation, a unifying theme emerges: livestock producers face interconnected market and production risks, and their ability to respond effectively depends on access to information, decision-making supporting tools, and structured marketing opportunities. Together, these studies illustrate how research can reduce uncertainty and support evidence-based strategies that help producers navigate complex health management and marketing environments, ultimately enhancing resilience in livestock systems.

Enhancing resilience in livestock systems

Managing risk in livestock systems requires producers to balance multiple considerations: ensuring animal health and welfare, evaluating disease risks, implementing biosecurity to safeguard production, and weighing economic motivations such as intervention costs and anticipated returns. Whether confronting emerging threats like JEV or managing endemic issues like BRD, producers weigh the perceived likelihood and impact of disease, the costs of preventive or therapeutic interventions (e.g., biosecurity upgrades, metaphylaxis), and the expected benefits, including improved health outcomes, regulatory compliance, and financial returns through price premiums, improved performance, or reduced losses. These decisions are rarely driven by a single factor; rather, they reflect complex trade-offs shaped by personal experience and values, as well as external pressures such as market incentives, consumer demand, and policy initiatives, such as those promoting antimicrobial stewardship.

Given the importance of the swine industry to the U.S. economy (USDA ERS, 2024), a potential JEV incursion could have significant impact, particularly considering the susceptible immune status of the U.S. swine herd. Chapter 2 presented a rapid systematic review of the

literature, synthesizing insights into what is known about JEV disease process dynamics, detection methods, control and preventive options, and potential impacts in swine species. Access to this evidence is essential for making informed decisions that minimize production and market risks within the swine sector, and for identifying research priorities where insufficient information limits the ability to draw conclusions and create effective preparedness plans. Key areas of uncertainty include the efficacy of biosecurity and surveillance measures, vaccine accessibility and licensure status, the degree (if any) of cross-protection between vaccine strains and other JEV strains or flaviviruses, the role of feral swine in virus spread and establishment, and considerations related to food safety, economic impacts, and preparedness planning at the industry (or national) level. This knowledge synthesis highlights critical research needs and supports the development of evidence-based strategies to strengthen both U.S. preparedness and response capacity in the event of a potential JEV incursion.

Although JEV is not currently present in the U.S. and thus poses no immediate risks to swine producers, the possibility of introduction has been demonstrated through formal risk assessments evaluating multiple pathways and international trade activities (Oliveira et al., 2018; Oliveira et al., 2019; Dixon et al., 2024). Transportation of infected mosquito larvae or eggs in imported goods, as well as movement of infected adult mosquitoes via aircraft, were identified as the routes posing the greatest risk for JEV entry into different regions of the U.S. (Dixon et al., 2024). If established, JEV could impose severe agricultural risks, including production losses due to reproductive failure in sows, human resource impacts resulting from severe clinical disease among producers and community and market disruptions caused by potential trade restrictions, reduced consumer confidence, and price volatility. The extent of these impacts would most likely depend on the degree of preparedness, including capacity for early detection,

containment, traceability, and adaptive management. The U.S. Disease Response Strategy: Japanese Encephalitis (U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Veterinary Services (USDA APHIS VS), 2024) reports that no USDA-licensed vaccine is currently available for swine or other species in the U.S. Yet, the strategy acknowledges that vaccination of swine, the amplifying host, can prevent reproductive losses in this specie and indirectly protect humans and other animals by reducing the transmission, since treatment for infected humans is only supportive. Despite recognizing that a JEV introduction in the U.S. would likely experience delayed detection due to a low level of suspicion among one-health professionals and potential serologic cross-reactivity between JEV and other flaviviruses — factors that could allow an enzootic transmission cycle to become established before detection — the U.S. currently has no active surveillance system for JEV. If such enzootic transmission cycle were stablished, eradication would be highly unlikely. Accordingly, the current response strategy focuses on managing the outbreak to the extent possible through biosecurity measures, vector control, access to no cost diagnostic test for animals displaying JEV-suggestive clinical signs, and monitoring the disease with minimal regulatory intervention. While producer-level incentives to adopt JEV preventive measures remain low in the absence of perceived risk, the current lack of proactive surveillance and licensed vaccines underscores a critical gap in national preparedness. These deficiencies highlight a need for proactive initiatives at the government level to invest in robust preparedness and surveillance strategies against JEV to strengthen resilience and safeguard the sustainability of the U.S. swine industry.

Contrastingly, while JEV represents an emerging foreign animal disease with uncertain but potentially devastating consequences, BRD illustrates the challenges of managing an endemic and impactful disease in a different commodity group, cattle. Currently, BRD continues

to be the most frequent and costly disease in U.S. feedlots, and decisions around metaphylaxis use reflect the balancing act stakeholders face between safeguarding animal health, meeting antimicrobial stewardship expectations, and maintaining economic viability. The survey of veterinarians and feedlot managers presented in Chapter 3 highlights how perceptions of disease risk, practical management considerations, and market incentives shape metaphylaxis practices, thereby influencing both production outcomes and the stability of downstream markets.

From a production standpoint, BRD remains the leading cause of morbidity, mortality, and performance losses in U.S. feedlot cattle (Griffin, 1997; Smith 1998; Johnson and Pendell, 2017), and metaphylaxis treatment at arrival represents a critical management strategy to reduce the uncertainty of disease outcomes, specifically in high-risk cattle. By examining how veterinarians and feedlot managers assess BRD risk and make metaphylaxis decisions for cattle deemed at medium risk, the survey identifies key factors influencing health management under uncertainty and highlights opportunities to strengthen decision-making with improved predictive tools, information transfer, and research-based evidence. From a market risk perspective, antimicrobial use is increasingly scrutinized by consumers, regulators, and packers, meaning that misaligned practices risk eroding consumer confidence, restricting market access, reducing price premiums, and prompting stricter regulations. Insufficient control of BRD can further destabilize markets through reduced carcass weight and quality, longer feeding periods to reach finishing weight, (Holland et al., 2010; Blakebrough-Hall et al., 2020), higher death loss, inconsistent supply, and price volatility. By characterizing how stakeholders balance these pressures, this project provides evidence of the challenges faced when making metaphylaxis decisions, informing stewardship programs and supporting the development of decision-making tools to refine antimicrobial use in cattle production. Strengthening communication across stakeholders

helps align management practices within the industry and with the evolving societal expectations, thereby ensuring consumer trust, adaptability to contemporary priority, and ultimately the long-term sustainability of the U.S. cattle industry.

Lastly, the research presented in Chapter 4 explored sale prices associated with different combinations of value-added program claims in calf lots sold through a national U.S. cattle auction market. By evaluating how combinations of health certification and value-added programs influence calf sale prices, this study provides evidence of the financial incentives associated with implementing specific management practices. From a production standpoint, value-added programs encourage investment in health and welfare measures such as vaccination, weaning protocols, preconditioning, and other husbandry practices that minimize stress, strengthen immune competency, reduce disease incidence, and support improved performance in the subsequent production phase (e.g., feedlot), ultimately promoting customer trust in the quality of the calf crop. From a market perspective, these programs create structured opportunities for producers to capture premiums, mitigate price volatility, and differentiate their product in a competitive marketplace. Speer et al. (2001) highlighted that producers should recognize the factors driving price variability and adopt source-verified, preconditioning programs, which reduce disease risk, enhance calf value, and help manage market uncertainty while capturing additional economic benefits. By quantifying the relationship between program participation and price outcomes, this research informs producer decision-making and supports evidence-based adoption of strategies that simultaneously enhance herd health and the economic resilience of the U.S feeder calf industry.

Taken together, the work presented in this dissertation demonstrate the multiple pathways through which outcomes research can inform decision-making and enhance the resilience of

livestock systems by helping producers and other stakeholders to more effectively manage agricultural risks and adapt to contemporary challenges.

The role of information in shaping behavior

Across these contexts, access to timely, accurate, and trusted information emerges as a key enabler of behavioral change and adjustment of management strategies that propel agriculture to continue to evolve toward improved animal welfare, production efficiency, and sustainability (economic, environmental, and social). When information is lacking or ambiguous, the motivation to adopt preventive or value-creating strategies weakens, hindering progress toward improved animal production that is in line with contemporary societal values.

Information plays a pivotal role in shaping producer perceptions and actions. To be effective, information must not only be generated through evidence-based approaches but also disseminated through outreach strategies that translate scientific knowledge into practical, applied guidance. In the case of JEV introduction risk in the U.S. (Chapter 2), the absence of outbreak experience, minimal government-led education and surveillance, and a lack of market incentives for proactive prevention contribute to low perceived risk and limited preparedness among both producers and officials. This occurs despite epidemiological evidence of U.S. vulnerability to JEV emergence. In the BRD metaphylaxis study (Chapter 3), producers' decisions are influenced not only by disease risk but also by market conditions (e.g., drug and cattle prices) and access to reliable risk-classification information. Respondents cited uncertainty in BRD risk assessment as a barrier to reducing metaphylaxis use, highlighting the importance of sharing clear and credible information, not only across production phases regarding cattle history, but also across professionals within production phases, to enhance consistency and support judicious antimicrobial use in disease risk management practices. The value-added

program study (Chapter 4) emphasizes the importance of market information, specifically regarding variability and reliability of price premiums. When these premiums are clearly communicated and consistently realized, they can incentivize producers to adopt additional certifications and management practices that benefit the broader industry. This benefits the industry not only by ensuring a reliable supply that meets current market demands — signaled by buyers paying premiums to producers who implement preferred management practices — but also by simultaneously promoting animal health, and information transfer between production phases, ultimately strengthening consumer trust in livestock husbandry practices.

In all three studies reported in this dissertation, it is clear that U.S. livestock systems can benefit tremendously from continued improvements in information access and dissemination. Evidence generated through research provides the foundation for understanding disease risks, production practices, and market opportunities, while effective outreach — through extension services, industry programs, and professional networks — translates this knowledge into actionable guidance and consistency in practices across industry stakeholders. By reducing uncertainty and aligning management strategies with scientific evidence and market signals, such information strengthens decision-making, encourages the adoption of value-creating practices, and ultimately enhances the resilience and sustainability of U.S. livestock industries as a whole.

Future directions

Several key areas emerge where future research and coordinated action of stakeholders could further strengthen risk management, information flow, and resilience within the U.S. livestock systems. One critical knowledge gap identified through the rapid systematic review on the role of swine in JEV transmission (Chapter 2) concerns the potential involvement of feral swine in the JEV transmission cycle, particularly within the U.S. context of intensive, diverse

swine production systems and widespread feral swine populations. Feral swine are invasive and highly adaptable, being reported in up to 48 U.S. states (Glow, Snow, and Vercauteren, 2020). In 2020, damage and control costs attributed to feral swine in 13 states exceeded 650 million USD (McKee et al., 2023). Moreover, feral swine harbor a broad range of pathogens — Miller et al. (2017) identified 27 OIE-listed terrestrial pathogens to be present in North American feral swine populations. Between 2002 and 2012, domestic swine farms in the U.S. experienced a 58% increase in co-occurrence with feral swine, with an estimated 1.3% annual rate increase (Miller et al., 2017). Beyond their potential role in domestic disease transmission to different livestock species (Miller et al., 2017; Glow, Snow, and Vercauteren, 2020), feral swine could serve as important introduction route (from neighboring countries) and/or establishment mechanism (acting as reservoirs or amplifying hosts) for other transboundary disease of significant economic and animal health impact, including JEV, New World Screwworm, Classical Swine Fever, and Foot-and-Mouth disease. These risks highlight the critical need for a much deeper understanding of feral swine in the U.S., particularly given how little is currently known about their population dynamics, movement ecology, and pathogen carriage. Species-specific (i.e., *Sus scrofa*) information on disease susceptibility, pathology, and mechanisms of transmission between domestic and feral swine remains sparse. Filling these knowledge gaps is essential to inform effective surveillance, risk assessments, and preparedness strategies, ultimately supporting the resilience of the U.S. livestock industry.

Building on findings from the survey of veterinary and feedlot managers regarding perceptions of metaphylaxis decision-making for cattle at medium risk of BRD (Chapter 3), and from the analysis of auction sale premiums associated with value-added programs in feeder calves (Chapter 4), future research should explore how enhanced traceability systems could

strengthen evidence-based disease management decisions in U.S. livestock systems. Animal traceability remains underutilized in the U.S. and represents a critical opportunity to improve information flow across the supply chains, enabling more timely and precise decisions regarding disease control, prevention, antimicrobial use, and market differentiation. In the context of BRD, improved data transfer between production stages could support more informed management decisions and was proposed by surveyed feedlot professionals as a practice that could reduce metaphylaxis use during this production phase. Similarly, research evaluating the economic value of traceability (eID) — quantifying both direct returns (e.g., sale premiums, reduced treatment costs, improved productivity) and indirect, industry-wide benefits (e.g., market access, consumer confidence, and biosecurity readiness) — could help producers assess whether implementing eID provides added value beyond improving disease management decisions.

Given that U.S. livestock sectors differ widely in their degree of vertical integration and information sharing, the adoption of traceability systems faces significant structural challenges. In less integrated industries, such as beef cattle, the costs of implementing traceability are often incurred by individual producers, while the benefits—such as improved market access, disease control, and consumer confidence—are distributed across the entire production chain. Future work should therefore investigate governance models and incentive structures (e.g., marketability and value-added to eID cattle) that equitably distribute the costs and benefits of traceability adoption among stakeholders. Specifically, studies examining how traceability data can inform risk-based interventions, such as targeted metaphylaxis decisions or other disease management practices, would directly support more effective disease control strategies. Additionally, identifying mechanisms to link traceability adoption with measurable economic value could enhance producer participation and support value-added programs within the U.S.

livestock sector. Such efforts would help advance disease management, antimicrobial stewardship, and market transparency across the broader U.S. livestock industry.

While each study presented in this dissertation raises its own logical avenues for future work — whether addressing unanswered questions from the chosen research approach or exploring new issues revealed by the findings — the additional conclusion that “future research is needed” is frequently claimed by researchers in a variety of study areas and should not be seen as an evasion or insufficiency. Rather, it reflects a reality that livestock production systems operate within dynamic biological, economic, and societal environments, where new challenges and priorities continually emerge. In such a context, research is not expected to yield definitive and permanent answers; instead, it serves as an iterative process of discovery, adaptation, and refinement.

Through systematic processes, outcomes research identifies inefficiencies, reveal opportunities for improvement, reduces environmental and social impacts, and generates knowledge that informs practical, evidence-based solutions that are in line with evolving societal expectations, regulatory pressures, and market conditions. By strengthening the evidence base for producer decision-making and policy development, research enhances the resilience, adaptability, and long-term sustainability of U.S. livestock systems. Continued investment in research and extension is therefore essential to advance animal health and welfare, safeguard economic viability, and maintain consumer trust in an increasingly dynamic agricultural landscape.

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Appendix A - Veterinarian Survey



Beef cattle veterinarians,

As a valued member of the cattle feeding industry, we seek your input on a survey which aims to understand the data and information that are used to make decisions regarding metaphylaxis use for Bovine Respiratory Disease (BRO) in feedlot/feeder cattle, particularly in cattle where the metaphylaxis decision is most challenging. Specifically, we want to elicit your professional opinions and recommendations on specific questions/ matters regarding the use of metaphylaxis in medium-risk cattle.

This study, Promoting Antimicrobial Stewardship Through Improved Knowledge On The Subset Of Feeder Cattle In Which The Value Of Metaphylaxis-use Is Most Uncertain, is led by veterinary faculty at Kansas State University and funded by the Foundation for Food & Agriculture Research - International Consortium for Antimicrobial Stewardship in Agriculture (ICASA) with matching from cattle feeding and veterinary companies, as a public-private partnership with an overarching goal of documenting and promoting antimicrobial stewardship for metaphylaxis in our industry. A similar survey will be completed by feedlot managers.

This survey should take approximately 15-30 minutes. We kindly ask that you complete this survey no later than 04/30/2024.

For questions or concerns about this survey, please contact Drs. Natalia Cernicchiaro (ncernic@vet.k-state.edu), David Renter (renter@vet.k-state.edu) or Christy Hanthorn (hanthorn@vet.k-state.edu).

We greatly appreciate your willingness to participate and provide data to help improve our profession and industry.

Sincerely, Natalia Cernicchiaro, David Renter and Christy Hanthorn College of Veterinary Medicine, Kansas State University

With input from advisory council members: Drs. Mike Apley, Shawn Blood, Lonty Bryant, Miles Theurer, Corbin Stevens, Josh Szasz and Alyssa Word.

Participation in this study is voluntary. You may decline to participate or stop participation at any point throughout the study. Responses to this survey will be anonymized with all identifiers removed, results will be published in aggregate form and will not be used or distributed for future research studies. If at any time you do not wish to answer a survey question, you may skip to the next question without terminating the survey (except for the first question). All procedures have been approved by the Kansas State University Institutional Review Board (protocol #IRB-11898; /RB Contact Information: Lisa Rubin, Chair, Committee on Research Involving Human Subjects, 203 Fairchild Hall, Kansas State University, Manhattan, KS 66506, (785) □□□-3224; Brad Woods, Associate Vice President for Research Compliance, 203 Fairchild Hall, Kansas State University, Manhattan, KS 66506, (785) □□□-3224).

Veterinary Population Demographics

1. How many feedlots (include both finishing and starter/ grow yards) do you provide services for? Please answer with a numerical value only.

These questions refer to cattle in the MODERATE or MEDIUM risk classification (i.e., the type of cattle for which metaphylaxis need is most uncertain).

2. What criteria do you use to classify cattle as medium or moderate risk in your clients' operations?

3. For medium risk cattle only, in what percent of pens is the metaphylaxis decision made prior to cattle arrival (i.e., based only on procurement/ pre-arrival factors)? Please answer with numerical values only from 0-100.

Minimum percent of medium risk pens: _____

Maximum percent of medium risk pens: _____

Average percent of pens across all your feedlots: _____

4. For medium risk cattle only, in what percent of pens is the metaphylaxis decision made primarily based on purchase price or break-evens? Please answer with numerical values only from 0-100.

Minimum percent of medium risk pens: _____

Maximum percent of medium risk pens: _____

Average percent of pens across all your feedlots: _____

5. For medium risk cattle only, in how many feedlots was the metaphylaxis decision made? Categories are not mutually exclusive i.e., if one feedlot makes decisions about metaphylaxis prior to and after cattle arrival, then enter 1 for "prior to cattle arrival" and enter 1 for "after cattle arrival."

Number of feedlots: _____

Prior to cattle arrival (i.e., based only on procurement/ pre-arrival factors):

Primarily based on purchase price or break-evens: _____

After cattle arrival: _____

All of the above: _____

Other, please specify: _____

6.a. What level of impact do the following factors have on decisions regarding metaphylaxis use before cattle arrival in these medium risk type cattle only? (scale: 1 - low impact, 5 - high impact). Please select an answer for each factor. If the factor does not apply, please select Not used.

	1	2	3	4	5	Not used
Body weight	☐	☐	☐	☐	☐	☐
Sex	☐	☐	☐	☐	☐	☐
Region of origin	☐	☐	☐	☐	☐	☐
Market channel (e.g., sale barn, ranch direct, etc.)	☐	☐	☐	☐	☐	☐
Backgrounding/pre- conditioning	☐	☐	☐	☐	☐	☐
Prior experience with the producer	☐	☐	☐	☐	☐	☐
Shrink	☐	☐	☐	☐	☐	☐
Overall health condition	☐	☐	☐	☐	☐	☐
Distance/time transported	☐	☐	☐	☐	☐	☐
Season	☐	☐	☐	☐	☐	☐
Weather conditions	☐	☐	☐	☐	☐	☐
Animal welfare	☐	☐	☐	☐	☐	☐
Potential mortality	☐	☐	☐	☐	☐	☐
Price of the metaphylaxis drug	☐	☐	☐	☐	☐	☐

Purchase price of cattle	☐	☐	☐	☐	☐	☐
Number of home pens	☐	☐	☐	☐	☐	☐
Number of head per pen	☐	☐	☐	☐	☐	☐
Labor availability	☐	☐	☐	☐	☐	☐
Cattle ownership (customer vs feedlot)	☐	☐	☐	☐	☐	☐
Concerns about antimicrobial resistance in animals	☐	☐	☐	☐	☐	☐
Concerns about antimicrobial resistance in people	☐	☐	☐	☐	☐	☐

6.b. What level of impact do the following factors have on decisions regarding metaphylaxis use after cattle arrival in these medium risk type cattle only? (Scale: 1 – low impact, 5 – high impact). Please select an answer for each factor. If the factor does not apply, please select Not used.

	1	2	3	4	5	Not used
Body weight	☐	☐	☐	☐	☐	☐
Sex	☐	☐	☐	☐	☐	☐
Region of origin	☐	☐	☐	☐	☐	☐
Market channel (e.g., sale barn, ranch direct, etc.)	☐	☐	☐	☐	☐	☐
Backgrounding/pre- conditioning	☐	☐	☐	☐	☐	☐
Prior experience with the producer	☐	☐	☐	☐	☐	☐
Shrink	☐	☐	☐	☐	☐	☐
Overall health condition	☐	☐	☐	☐	☐	☐
Distance/time transported	☐	☐	☐	☐	☐	☐
Season	☐	☐	☐	☐	☐	☐
Weather conditions	☐	☐	☐	☐	☐	☐
Animal welfare	☐	☐	☐	☐	☐	☐
Potential mortality	☐	☐	☐	☐	☐	☐
Price of the metaphylaxis drug	☐	☐	☐	☐	☐	☐

Purchase price of cattle	☐	☐	☐	☐	☐	☐
Number of home pens	☐	☐	☐	☐	☐	☐
Number of head per pen	☐	☐	☐	☐	☐	☐
Labor availability	☐	☐	☐	☐	☐	☐
Cattle ownership (customer vs feedlot)	☐	☐	☐	☐	☐	☐
Concerns about antimicrobial resistance in animals	☐	☐	☐	☐	☐	☐
Concerns about antimicrobial resistance in people	☐	☐	☐	☐	☐	☐

7.a. What subjective information that is obtained about a group of medium risk cattle only, prior to their arrival at the feedlot, is used to make decisions about metaphylaxis? (e.g., visual assessments such as "fleshy", "skinny", "agitated", "stale", or "exhausted" are subjective information) .

Factor 1: _____

Factor 2: _____

Factor 3: _____

Factor 4: _____

Factor 5: _____

7.b. What subjective information that is obtained about a group of medium risk cattle only, after their arrival at the feedlot, is used to make decisions about metaphylaxis use? (e.g., visual

assessments such as “fleshy”, “skinny”, "agitated", "stale", or "exhausted" are subjective information)

Factor 1: _____

Factor 2: _____

Factor 3: _____

Factor 4: _____

Factor 5: _____

8. a. Who (person’s role or job title) do **you** recommend should have input, before and after cattle’s arrival at the feedlot, regarding the decision to use metaphylaxis in these medium risk type cattle **only**? (select all that apply)

	Select all that apply	
	Before cattle arrive: (1)	After cattle arrive: (2)
Veterinarian (1)	☐	☐
Feedlot manager (2)	☐	☐
Hospital crew lead (3)	☐	☐
Other, please specify (4) _____	☐	☐
Other, please specify (5) _____	☐	☐

8.b. Who do you recommend makes the final decision of whether or not to use metaphylaxis in a pen of medium risk cattle only? (indicate one person’s role or job title).

9. What objective data do you wish you or your feedlots had available, or had available more often or more accurately, when making decisions about metaphylaxis use in these medium risk type cattle only, and explain how would each of these factors influence the decision?

	Relevant Factor		If yes, please specify below. If no, please enter NA.
	Yes	No	How it influences the decision?
Weaning date	☐	☐	
Record of previous rations	☐	☐	
Feed intake records	☐	☐	
Vaccination records	☐	☐	
Treatment records	☐	☐	
Other, please specify	☐	☐	
Other, please specify	☐	☐	
Other, please specify	☐	☐	

10. What subjective information do you wish you or your feedlots had available, or had available more often or more accurately, when making decisions about metaphylaxis use in these medium risk type cattle only, and explain how would each of these factors influence the decision?

	Relevant Factor		If yes, please specify below. If no, please enter NA.
	Yes	No	How it influences the decision?
Fleshy or Skinny	☐	☐	
Other, please specify	☐	☐	
Other, please specify	☐	☐	
Other, please specify	☐	☐	

11.a. Considering these cattle with medium or moderate BRD risk, what would be your expected morbidity per pen if metaphylaxis were not applied?

- ☐ $\leq 5.0\%$
- ☐ $> 5.0\%$ and $\leq 10.0\%$
- ☐ $> 10.0\%$ and $\leq 15.0\%$

- ☐ >15.0% and ≤20.0%
- ☐ >20.0% and ≤25.0%
- ☐ >25.0% and ≤30.0%
- ☐ >30.0%

11.b. Considering these cattle with medium or moderate BRD risk, what would be your expected mortality per pen if metaphylaxis were not applied?

- ☐ ≤1.0%
- ☐ >1.0% and ≤2.0%
- ☐ >2.0% and ≤3.0%
- ☐ >3.0% and ≤4.0%
- ☐ >4.0% and ≤5.0%
- ☐ >5.0%

12. Based on your experience, and given changes in industry (e.g., cattle costs, drug costs), what percent of pens that DID NOT initially receive metaphylaxis, in hindsight, should have had it? Please answer with numerical values only from 0-100.

In 2023, what percent of pens? _____

Historically (e.g., 2018-2020), what percent of pens? _____

13. Based on your experience, and given changes in industry (e.g., cattle costs, drug costs), what percent of pens that DID initially receive metaphylaxis, in hindsight, may not have needed it? Please answer with numerical values only from 0-100.

In 2023, what percent of pens? _____

Historically (e.g., 2018-2020), what percent of pens? _____

14. In your opinion, what factors could reduce metaphylaxis use in medium risk cattle only?

BRD Management

15.a. Approximately what percentage of the feedlots that you consulted for in 2023 used metaphylaxis in at least one pen of cattle? Please answer with a numerical value only from 0-100.

15. b. Within those feedlots that used metaphylaxis, approximately what percentage of pens within a feedlot received metaphylaxis in 2023? Please answer with numerical values only from 0-100.

Minimum percent of pens within a feedlot: _____

Maximum percent of pens within a feedlot: _____

Average percent of pens: _____

15.c. Within those feedlots that used metaphylaxis, how does the proportion of pens that received metaphylaxis compare to 3 to 5 years ago (e.g., during 2018 to 2020)?

- ☐ More than 20% higher in 2023 compared to 3 to 5 years ago.
- ☐ 10-20% higher in 2023 compared to 3 to 5 years ago.
- ☐ Less than 10% higher in 2023 compared to 3 to 5 years ago.
- ☐ Similar proportion in 2023 compared to 3 to 5 years ago.
- ☐ Less than 10% lower in 2023 compared to 3 to 5 years ago.
- ☐ 10-20% lower in 2023 compared to 3 to 5 years ago.
- ☐ More than 20% lower in 2023 compared to 3 to 5 years ago.

16. What percentage of cattle across all the feedlots that you consulted for in 2023 fell into the following BRD risk categories? Please answer with numerical values only from 0-100. Your total should add up to 100.

Risk class

Low BRD risk: _____

Medium BRD risk: _____

High BRD risk: _____

Other, please specify: _____

Other, please specify: _____

Other, please specify: _____

Other, please specify: _____

Total: _____

17. What percentage of feedlots that you consulted for in 2023 fed cattle in the following BRD risk categories? Please answer with numerical values only from 0-100.

Risk class	<u>Percentage</u> of feedlots that fed these cattle
Low BRD risk	
Medium BRD risk	
High BRD risk	
Other, please specify	
Other, please specify	
Other, please specify	
Other, please specify	

18. Across all the feedlots that you consulted for in 2023, what factors were used to determine BRD risk classifications for arriving cattle? Please answer with numerical values only from 0-100.

Risk class	For what <u>percentage</u> of pens?
Origin (e.g. geography, production-phase, etc.)	
Order buyer	
Weaning history	
Distance transported	
Pre-conditioning	
Weather conditions	
Arrival body weight	
Shrink	
Sex	
Other, please specify	
Other, please specify	
Other, please specify	

Other, please specify	
Other, please specify	

19. How does the BRD risk classification vary from feedlot to feedlot? Please describe/explain.

20. What is the approximate number of cattle per day each pen rider is responsible for evaluating across all the feedlots you consulted for in 2023? Please answer with numerical values only.

Minimum number of cattle per day: _____

Maximum number of cattle per day: _____

Average number of cattle per day: _____

Feedlot Population Demographics

21. What is the smallest feedlot size (one-time capacity) you provided input on metaphylaxis to during 2023? Please indicate the number of head or estimate if you are unsure. Please answer with a numerical value only.

22. What is the largest feedlot size (one-time capacity) you provided input on metaphylaxis to during 2023? Please indicate the number of head or estimate if you are unsure. Please answer with a numerical value only.

23. What is the estimated sum total of all the animals in all the feedlots that you consulted for in 2023? Please answer with a numerical value only.

24. When considering all the cattle that you consulted for in 2023, what is your estimate of the percentage of cattle that fell into each ownership category for the majority of their time in the feedlot? Please answer with numerical values only from 0-100. Your total should add up to 100.

Exclusively owned by the customer: _____

Exclusively owned by the feedlot/company: _____

Joint ownership: _____

Total: _____

Cattle Population Demographics

25.a. Please estimate what percentage of cattle that you provided veterinary services for during 2023 fell into each of the following age categories. Please answer with numerical values only from 0-100. Your total should add up to 100.

Calves: _____

Yearlings: _____

Other: _____

Total: _____

25.b. Please estimate what percentage of cattle that you provided veterinary services for during 2023 fell into each of the following sex categories. Please answer with numerical values only from 0-100. Your total should add up to 100.

Steers: _____

Bulls: _____

Heifers: _____

Spayed heifers: _____

Total: _____

25. c. Please estimate what percentage of cattle that you provided veterinary services for during 2023 fell into each of the following breed categories. Please answer with numerical values only from 0-100. Your total should add up to 100.

Beef breeds: _____

Dairy breeds: _____

Beef-on-dairy cross: _____

Total: _____

25. d. Please estimate what percentage of cattle that you provided veterinary services for during 2023 came from the following origins. Please answer with numerical values only from 0-100. Your total should add up to 100.

U.S. : _____

Canada : _____

Mexico : _____

Total : _____

26. How soon following arrival to the feedlot do you recommend cattle are processed (e.g., within 24, 48, 72 hours)?

Minimum time in hours after arrival: _____

Maximum time in hours after arrival: _____

Estimate the average time in hours after arrival when processing actually occurs: _____

Veterinarian Demographics

27. To how many feedlots did you personally provide consultation about metaphylaxis decisions during 2023? Please specify the number of feedlots. Please answer with a numerical value only.

28. How many of the feedlots for which you consulted on metaphylaxis decisions in 2023 also had other veterinarians providing consultation on metaphylaxis decisions? Please specify the number of feedlots. Please answer with a numerical value only.

29. Please mark all state(s) in which the feedlots you consulted for in 2023 were located:

- | | | | | | |
|--------------------------------|--------------------------------|-------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|
| ☐ Alaska | ☐ Hawaii | ☐ Maryland | ☐ New Hampshire | ☐ Pennsylvania | ☐ Washington |
| ☐ Arizona | ☐ Idaho | ☐ Massachusetts | ☐ New Jersey | ☐ Rhode Island | ☐ West Virginia |
| ☐ Arkansas | ☐ Illinois | ☐ Michigan | ☐ New Mexico | ☐ South Carolina | ☐ Wisconsin |

- | | | | | | |
|-----------------------------------|---------------------------------|-----------------------------------|--------------------------------------|------------------------------------|-------------------------------|
| ☐ California | ☐ Indiana | ☐ Minnesota | ☐ New York | ☐ South Dakota | ☐ Wyoming |
| ☐ Colorado | ☐ Iowa | ☐ Mississippi | ☐ North Carolina | ☐ Tennessee | |
| ☐ Connecticut | ☐ Kansas | ☐ Missouri | ☐ North Dakota | ☐ Texas | |
| ☐ Delaware | ☐ Kentucky | ☐ Montana | ☐ Ohio | ☐ Utah | |
| ☐ Florida | ☐ Louisiana | ☐ Nebraska | ☐ Oklahoma | ☐ Vermont | |
| ☐ Georgia | ☐ Maine | ☐ Nevada | ☐ Oregon | ☐ Virginia | |

30. How many years of feedlot practice experience do you have?

- ☐ <5 years
- ☐ 5-10 years
- ☐ 10-15 years
- ☐ 15-20 years
- ☐ >20 years

31.a. How many other DVMs work in your practice/group?

31. b. If you answered more than one for question 31a, how many of them are also responding to this survey? If no others from your practice/group are responding, does your response represent the other DVMs in your practice/group that you referred to in question 31a?

32. Please share any additional comments you may have.

This is the end of the survey. If you would like to change any of your previous answers, select the back button. If you are finished, please select the submit button to turn in your survey.

Appendix B - Feedlot Managers Surveys



Feedlot general managers,

Participation in this study is voluntary. You may decline to participate or stop participation at any point throughout the study. If at any time you do not wish to answer a survey question, you can skip to the next question without terminating the survey.

Responses to this survey are anonymous and no identifying information is collected at any point. Results will be published in aggregate form and will not be used or distributed for any other reason.

As a valued member of the cattle feeding industry, we seek your input on a survey which aims to understand the data and information that are used to make decisions regarding metaphylaxis use for Bovine Respiratory Disease (BRD) in feedlot/feeder cattle, particularly in the type of cattle, where the metaphylaxis decision is most challenging.

This survey should be completed by the individual feedlot manager at each location.

All procedures have been approved by the Kansas State University Institutional Review Board (Protocol #: IRB-11619; IRB Contact Information: Lisa Rubin, Chair, Committee on Research Involving Human Subjects, 203 Fairchild Hall, Kansas State University, Manhattan, KS 66506, (785) 843-3224; Brad Woods, Associate Vice President for Research Compliance, 203 Fairchild Hall, Kansas State University, Manhattan, KS 66506, (785) 843-3224).

This survey should take approximately 20 minutes. We kindly ask that you complete this survey no later than 2/15/2025.

For questions or concerns about this survey, please contact Drs. Natalia Cernicchiaro (ncernic@vet.k-state.edu), David Renter (drenter@vet.k-state.edu), or Christy Hanthorn (chanthorn@vet.k-state.edu).

We greatly appreciate your willingness to participate and provide data to help improve our industry.

Metaphylaxis Management

These questions pertain to the type of cattle for which the need for metaphylaxis is most uncertain, often classified as MODERATE or MEDIUM risk for Bovine Respiratory Disease (BRD). We acknowledge that risk classifications can vary; in this survey, moderate- or medium-risk refers to cattle that may ultimately be considered high risk for developing BRD and given metaphylaxis, although distinguishing clearly between high and low risk can be challenging.

1. What criteria are used to classify cattle as medium or moderate risk in your feedlot? Please describe.

2. For medium risk cattle only, in what percent of pens is the metaphylaxis decision made prior to cattle arrival (i.e., based only on procurement/pre-arrival factors)? Please answer with a numerical value only from 0-100.

Average percent of pens across the feedlot: _____

3. For medium risk cattle only, in what percent of pens is the metaphylaxis decision made primarily based on purchase price or break-evens? Please answer with a numerical value only from 0-100.

Average percent of pens across the feedlot: _____

4. When are objective data used to make decisions regarding metaphylaxis use? Please select all options that apply.

Before cattle arrive: _____

After cattle arrive: _____

Other, please specify: _____

5.a. Before cattle arrival, what level of impact do the following factors have on decisions regarding metaphylaxis use in these medium risk type cattle only? (Scale: 1 – low impact, 5 – high impact).

Please select an answer for each factor. If the factor does not apply, please select “Not used”.

	1	2	3	4	5	Not used
Body weight	☐	☐	☐	☐	☐	☐
Sex	☐	☐	☐	☐	☐	☐
Region of origin	☐	☐	☐	☐	☐	☐
Market channel (e.g., sale barn, ranch direct, etc.)	☐	☐	☐	☐	☐	☐
Backgrounding/pre- conditioning	☐	☐	☐	☐	☐	☐
Prior experience with the producer	☐	☐	☐	☐	☐	☐
Prior experience with sale barn	☐	☐	☐	☐	☐	☐
Shrink	☐	☐	☐	☐	☐	☐
Overall health condition	☐	☐	☐	☐	☐	☐
Distance/time transported	☐	☐	☐	☐	☐	☐
Season	☐	☐	☐	☐	☐	☐
Weather conditions	☐	☐	☐	☐	☐	☐
Animal welfare	☐	☐	☐	☐	☐	☐
Expected mortality	☐	☐	☐	☐	☐	☐

Price of the metaphylaxis drug	☐	☐	☐	☐	☐	☐
Purchase price of cattle	☐	☐	☐	☐	☐	☐
Number of home pens available	☐	☐	☐	☐	☐	☐
Number of head per pen	☐	☐	☐	☐	☐	☐
Labor availability	☐	☐	☐	☐	☐	☐
Pen conditions (mud)	☐	☐	☐	☐	☐	☐
Cattle ownership (customer vs feedlot)	☐	☐	☐	☐	☐	☐
Concerns about antimicrobial resistance in animals	☐	☐	☐	☐	☐	☐
Concerns about antimicrobial resistance in people	☐	☐	☐	☐	☐	☐

5.b. What other subjective information that is obtained about a group of medium risk cattle prior to their arrival at the feedlot is used to make decisions about metaphylaxis? (e.g., visual assessments such as “fleshy”, “skinny”, “agitated”, “stale”, or “exhausted” are subjective information).

Factor 1: _____

Factor 2: _____

Factor 3: _____

5.c. After cattle arrival, what level of impact do the following factors have on decisions regarding metaphylaxis use in these medium risk type cattle only? (Scale: 1 – low impact, 5 – high impact). Please select an answer for each factor. If the factor does not apply, please select “Not used”.

	1	2	3	4	5	Not used
Body weight	☐	☐	☐	☐	☐	☐
Sex	☐	☐	☐	☐	☐	☐
Region of origin	☐	☐	☐	☐	☐	☐
Market channel (e.g., sale barn, ranch direct, etc.)	☐	☐	☐	☐	☐	☐
Backgrounding/pre- conditioning	☐	☐	☐	☐	☐	☐
Prior experience with the producer	☐	☐	☐	☐	☐	☐
Prior experience with sale barn	☐	☐	☐	☐	☐	☐
Shrink	☐	☐	☐	☐	☐	☐
Overall health condition	☐	☐	☐	☐	☐	☐
Distance/time transported	☐	☐	☐	☐	☐	☐
Season	☐	☐	☐	☐	☐	☐
Weather conditions	☐	☐	☐	☐	☐	☐
Animal welfare	☐	☐	☐	☐	☐	☐
Expected mortality	☐	☐	☐	☐	☐	☐

Price of the metaphylaxis drug	☐	☐	☐	☐	☐	☐
Purchase price of cattle	☐	☐	☐	☐	☐	☐
Number of home pens available	☐	☐	☐	☐	☐	☐
Number of head per pen	☐	☐	☐	☐	☐	☐
Labor availability	☐	☐	☐	☐	☐	☐
Pen conditions (mud)	☐	☐	☐	☐	☐	☐
Cattle ownership (customer vs feedlot)	☐	☐	☐	☐	☐	☐
Concerns about antimicrobial resistance in animals	☐	☐	☐	☐	☐	☐
Concerns about antimicrobial resistance in people	☐	☐	☐	☐	☐	☐

5. d. What other subjective information that is obtained about a group of medium risk cattle after their arrival at the feedlot is used to make decisions about metaphylaxis use? (e.g., visual assessments such as “fleshy”, “skinny”, “agitated”, “stale”, or “exhausted” are subjective information)

Factor 1: _____

Factor 2: _____

Factor 3: _____

6. Considering medium risk cattle only, how soon do you process them following arrival to the feedlot (e.g., within 24, 48, 72 hours)?

Minimum time in hours after arrival: _____

Maximum time in hours after arrival: _____

Estimated average time in hours after arrival: _____

7. a. Who (person's role or job title) has input, before and after cattle arrival at your feedlot, regarding the decision to use metaphylaxis in these medium risk type cattle only? (select all that apply)

	Select all that apply	
	Before cattle arrive: (1)	After cattle arrive: (2)
Veterinarian (1)	☐	☐
Feedlot manager (2)	☐	☐
Hospital crew lead (3)	☐	☐
Other, please specify (4) _____	☐	☐
Other, please specify (5) _____	☐	☐

7. b. Who makes the final decision of whether to use metaphylaxis in a pen of medium risk cattle only? (indicate one person's role or job title).

8. What objective data or subjective information do you wish were available, or were available more often or more accurately, when making decisions about metaphylaxis use in these medium risk type cattle only, and explain how each of these factors would influence the decision?

	Relevant Factor	If yes, please specify below. If no, please enter NA.
--	-----------------	---

	Yes	No	How it influences the decision?
Weaning date	☐	☐	
Record of previous rations	☐	☐	
Feed intake records	☐	☐	
Vaccination records	☐	☐	
Treatment records	☐	☐	
Fleshy or skinny	☐	☐	
Other, please specify	☐	☐	
Other, please specify	☐	☐	
Other, please specify	☐	☐	

9. a. Considering these cattle with medium or moderate BRD risk, what would be your expected morbidity per pen if metaphylaxis were not applied? Please select all that apply.

- ☐ $\leq 5.0\%$
- ☐ $> 5.0\%$ and $\leq 10.0\%$
- ☐ $> 10.0\%$ and $\leq 15.0\%$
- ☐ $> 15.0\%$ and $\leq 20.0\%$
- ☐ $> 20.0\%$ and $\leq 25.0\%$
- ☐ $> 25.0\%$ and $\leq 30.0\%$
- ☐ $> 30.0\%$

9. b. Considering these cattle with medium or moderate BRD risk, what would be your expected mortality per pen if metaphylaxis were not applied? Please select all that apply.

- ☐ $\leq 1.0\%$
- ☐ $> 1.0\%$ and $\leq 2.0\%$
- ☐ $> 2.0\%$ and $\leq 3.0\%$
- ☐ $> 3.0\%$ and $\leq 4.0\%$
- ☐ $> 4.0\%$ and $\leq 5.0\%$
- ☐ $> 5.0\%$

10. Based on your experience, and given changes in industry (e.g., cattle costs, drug costs), what percent of pens that DID NOT initially receive metaphylaxis, in hindsight, should have had it? Please answer with numerical values only from 0-100.

In 2023, what percent of pens? _____

Historically (e.g., 2018-2020), what percent of pens? _____

11. Based on your experience, and given changes in industry (e.g., cattle costs, drug costs), what percent of pens that DID initially receive metaphylaxis, in hindsight, may not have needed it? Please answer with numerical values only from 0-100.

In 2023, what percent of pens? _____

Historically (e.g., 2018-2020), what percent of pens? _____

12. How concerned are you that antimicrobial use for metaphylaxis impacts animal health (e.g., drugs will stop working on cattle)? Please select one option only.

- ☐ Extremely concerned
- ☐ Moderately concerned
- ☐ Somewhat concerned
- ☐ Slightly concerned
- ☐ Not at all concerned

13. How concerned are you that antimicrobial use for metaphylaxis impacts human health (e.g., impacts on your workers or the public)? Please select one option only.

- ☐ Extremely concerned
- ☐ Moderately concerned
- ☐ Somewhat concerned
- ☐ Slightly concerned
- ☐ Not at all concerned

BRD Management

14. a. Based on your memory, please estimate what percentage of all pens within your feedlot received metaphylaxis in 2023? Please answer with a numerical value only from 0-100.

14. b. Based on your memory, how does the proportion of pens in your feedlot that received metaphylaxis in 2023 compare to 3 to 5 years ago (e.g., during 2018 to 2020)? Please select one option only.

- ☐ More than 20% higher in 2023 compared to 3 to 5 years ago.
- ☐ 10-20% higher in 2023 compared to 3 to 5 years ago.
- ☐ Less than 10% higher in 2023 compared to 3 to 5 years ago.
- ☐ Similar proportion in 2023 compared to 3 to 5 years ago.
- ☐ Less than 10% lower in 2023 compared to 3 to 5 years ago.
- ☐ 10-20% lower in 2023 compared to 3 to 5 years ago.
- ☐ More than 20% lower in 2023 compared to 3 to 5 years ago.

15. Based on your memory, what percentage of cattle in your feedlot in 2023 fell into the following BRD risk categories? Please answer with numerical values only from 0-100. Your total should add up to 100.

Risk class	Percentage of cattle
Low BRD risk	
Medium BRD risk	
High BRD risk	
Other, please specify	
Total	

16. What was the approximate number of cattle per day each pen rider was responsible for evaluating in 2023?

Average number of cattle per day: _____

Range of cattle per day: _____

Feedlot Population Demographics

17. What was your feedlot's one-time capacity in 2023? Please indicate the number of head or estimate if you are unsure. Please answer with a numerical value only.

18. How many home pens are in your feedlot? Please answer with a numerical value only.

19. What is the range of pen sizes (based on head count) in your feedlot? Please answer with numerical values only.

Minimum: _____

Maximum: _____

20. In 2023, what is your estimate of the percentage of cattle in your feedlot that fell into each ownership category for most of their time in the feedlot? Please answer with numerical values only from 0-100. Your total should add up to 100.

Exclusively owned by the customer: _____

Exclusively owned by the feedlot/company: _____

Joint Ownership: _____

Total: _____

Cattle Population Demographics

21. a. Based on your memory, please estimate what percentage of cattle in your feedlot during 2023 fell into each of the following age categories. Please answer with numerical values only from 0-100. Your total should add up to 100.

Calves: _____

Yearlings: _____

Other: _____

Total: _____

25.b. Based on your memory, Please estimate what percentage of cattle in your feedlot during 2023 fell into each of the following sex categories. Please answer with numerical values only from 0-100. Your total should add up to 100.

Steers: _____

Bulls: _____

Heifers: _____

Spayed Heifers: _____

Total: _____

25.c. Based on your memory, Please estimate what percentage of cattle in your feedlot during 2023 fell into each of the following breed categories. Please answer with numerical values only from 0-100. Your total should add up to 100.

Beef breeds: _____

Dairy breeds: _____

Beef-on-dairy cross: _____

Total: _____

Feedlot Manager Demographics

22. How many feedlots (include both finishing and starter/grow yards) do you manage? Please answer with a numerical value only.

23. How many years have you been a feedlot manager or in your current role?

☐ <5 years

☐ 5-10 years

☐ 10-15 years

- ☐ 15-20 years
- ☐ >20 years

24. In what state is the feedlot that you manage located?

25. Please share any additional comments you may have.

This is the last question for this survey. If you would like to change any of your previous answers, select the back arrow button. If you are finished, please answer Question 26 and select the next arrow button.

26. Is there another feedlot you manage for which you would like to complete a survey?

- ☐ Yes
- ☐ No