PROCEEDINGS OF THE INAUGURAL ISESSAH CONFERENCE

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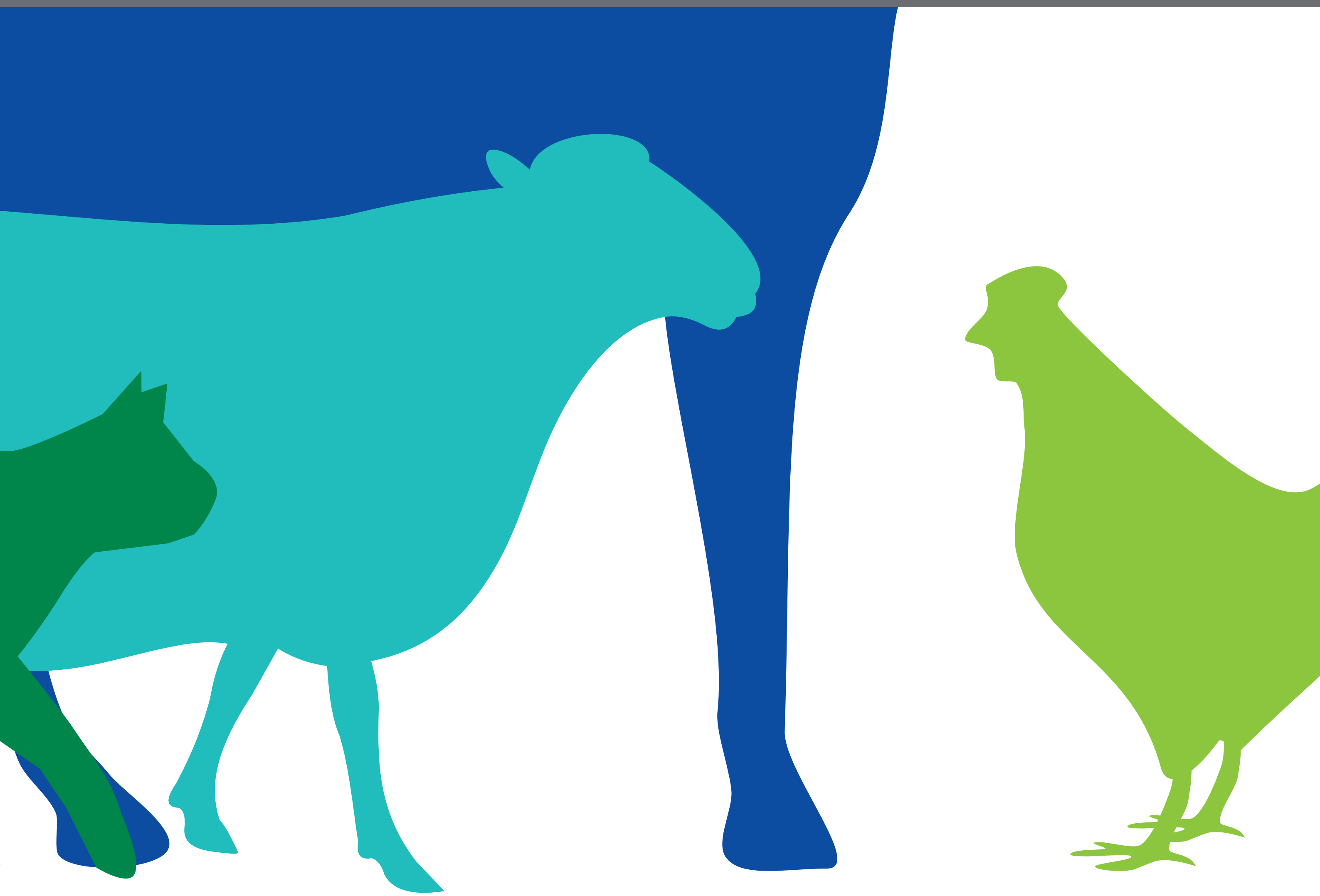

frontiers Research Topics

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PROCEEDINGS OF THE INAUGURAL ISESSAH CONFERENCE

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EDITORIAL
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Editorial: Proceedings of the Inaugural ISESSAH Conference

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Keywords: economics of animal health, social sciences of animal health, ISESSAH, animal diseases, animal health policies

Editorial on the Research Topic

Proceedings of the Inaugural ISESSAH Conference

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Tackling the challenge of supplying sufficient food for the increasing human population in an environmentally and ecologically sustainable manner is an important focus of public and private-sector policy makers. Livestock production chains play crucial roles in fulfilling the global sustainable development goals defined by the United Nations (1). Animal diseases and animal welfare problems are considered as major barriers in achieving optimized production and profit levels where ecological and environmental damages are minimized. Emerging and reemerging transboundary diseases that are often highly contagious [such as foot-and-mouth disease (FMD), peste des petits ruminants (PPR), African swine fever (ASF), and highly-pathogenic avian influenza (HPAI)] continue to threaten livestock industries in both developed and developing counties. Similarly, other infectious and non-infectious diseases continue to impose a socioeconomic burden on food production chains and on the wider social economy in many countries.

To tackle animal diseases, resolve animal welfare problems, and mitigate their environmental and socioeconomic burden, continuously supplied quantitative and qualitative socioeconomic research is crucial to support policy-making process. To achieve this goal, the International Society for Economics and Social Sciences of Animal Health (ISESSAH) was established in 2017 and its inaugural conference was held in March 2017 in Avimore, Scotland. The current Research Topic is devoted to 11 papers from among those presented in the first ISESSAH conference. Papers presented in this Research Topic cover broad but relevant areas of focus that can be grouped into three main categories: (1) economic assessment and managerial decision analysis of production diseases; (2) economic and policy assessment of contagious transboundary animal diseases and zoonoses; and (3) human behavior in relation to animal health and market analysis.

ECONOMIC ASSESSMENT AND MANAGERIAL DECISION ANALYSIS OF PRODUCTION DISEASES

Romero et al. assessed the financial impact of subclinical mastitis in dairy farms in Colombia. The authors showed that mastitis imposed a greater financial loss on small and medium-sized dairy farms than on larger farms, and they highlighted the gap in our understanding of the costs and effectiveness of on-farm intervention measures. Niemi et al. reported the costs of postpartum dysgalactia syndrome (PPDS) and locomotory disorders of sows due to their impacts on productivity and replacement rates in Finland. Using a stochastic dynamic programming model that maximized the return on sow space unit, they demonstrated that PPDS and locomotory disorders imposed financial losses of €29.1 and €11.5 per housed sow, respectively, during her lifetime.

By conducting a literature review, consulting experts, and using a partial budget model, Alvåsen et al. presented an analysis on animal welfare and the economic aspects of using nurse sows for equalizing the number of piglets per nursing sow in Sweden. They found that the lactation period of sows in Sweden is longer than in other countries, which can negatively affect sow body condition, damage teats and result in shoulder ulcers. Under nursing management practices, the piglet mortality rate could be reduced and higher financial returns generated, but the separating and mixing of piglets is stressful for piglets.

Hagerman et al. employed and assessed three estimation techniques for determining the value of replacement beef cows under data availability constraint, namely: hedonic pricing, vector error correction modeling, and cost of production. After analyzing the performance of each of these livestock valuation techniques, the authors concluded that the selection of a valuation method might need to vary based on data availability and characteristics of the livestock being valued, in terms of quality and age.

ECONOMIC AND POLICY ASSESSMENT OF CONTAGIOUS TRANSBOUNDARY ANIMAL DISEASES AND ZOONOSES

A study by Truong et al. focused on assessing the economic impact of FMD outbreaks in beef and dairy farms in Long An and Tay Ninh provinces in South Vietnam. The authors also evaluated the economic justification of a biannual vaccination strategy to prevent and eradicate FMD. Results showed that FMD vaccination had a better net present value in large dairy farms than in small ones and had a 20-times higher net present value in dairy farms than in beef farms. They concluded that a biannual vaccination strategy is economically justifiable in dairy farms, but there was uncertainty about its justification in beef farms. Featuring FMD as a serious threat for international trade, Feng et al. assessed sectoral-level impacts of control measures on FMD outbreaks in FMD-free countries using a partial equilibrium model of the agricultural sector known as FAPRI-UK. By combining epidemiologic and economic modeling frameworks, the authors simulated and assessed the consequence of two control strategies of "stamping out" and "vaccinate-to-die" on commodity market prices in the UK. Given the assumptions used, their analyses showed that the price and value of output impacts were lower under the "vaccinate-to-die" strategy compared to the "stamping out" strategy.

Focusing on another highly contagious disease control policy, Thuy Nguyen et al. conducted a stakeholder survey of live bird markets and assessed the impact of closure of these markets as a mitigation measure for HPAI in Viet Nam. Their analysis demonstrated that it is very likely that trading outside of formal markets will occur in the event of a temporary live animal market closure. Hence, the authors concluded that strict enforcement, engagement with stakeholders, and adequate communication are important prerequisites before market closure policy is introduced. By merging value chain analysis and participatory approaches to developing innovative tools for analyzing constraints to information flow, Antoine-Moussiaux et al. proposed a field-based perspective on value chain applications to HPAI prevention and control as an example of animal health systems within a One Health framework.

Munsick et al. assessed the costs and benefits of vaccinating individual sheep flocks against bluetongue virus using a stochastic simulation modeling approach with a representative rangeland sheep operation in the Big Horn Basin of the state of Wyoming in the United States. They compared the costs, benefit, and net impacts of both a killed virus vaccine and a modified-live virus vaccine under various outbreak scenarios. Results showed that a killed virus vaccine was not economically justifiable for producers in areas with a low probability of outbreaks. A modified-live vaccine has not been manufactured in Wyoming and needs rigorous authorization before legal use can start.

HUMAN BEHAVIOR IN RELATION TO ANIMAL HEALTH AND MARKET ANALYSIS

Under our third category of papers, by using exploratory and then face-to-face interviews, Ciaravino et al. investigated the perceptions, opinions, attitudes, and beliefs of farmers and veterinarians influencing the effectiveness of the bovine tuberculosis (bTB) eradication programme in Spain. The authors demonstrated the value of qualitative research for assessing the effectiveness of health interventions that are influenced by social and behavioral factors rather than biological ones. Focusing on market behavior and drivers of live cattle prices in Central Cameroon, Motta et al. used a quantitative framework, namely a generalized additive mixed-effect model, to identify the factors contributing to cattle price. Their findings indicated that the age and sex of the cattle traded were important drivers of price along with local human and bovine population densities.

Overall, the collection of papers in this Research Topic provides a good read on a number of important aspects of socioeconomics of animal health and welfare. This reflects a fraction of the many valuable efforts at the global level that are devoted to improving our knowledge and filling existing gaps in the literature of the economics of animal health and welfare. The authors of this Editorial and the board of the ISESSAH have great hope that the research being conducted and presented in future Research Topics of ISESSAH as well as in other related initiatives will contribute to further closure of these knowledge gaps and support animal health policies.

AUTHOR CONTRIBUTIONS

BV drafted the editorial. BH had an advisory role and provided input at the designing stage of the Research Topic. JR, HH, and GG reviewed and revised the editorial and contributed to the reviewing and editing the papers published in the proceedings of the ISESSAH inaugural conference.

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EMPIRICAL STUDY
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A Stakeholder Survey on Live Bird Market Closures Policy for Controlling Highly Pathogenic Avian Influenza in Vietnam

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Extensive research in Vietnam and elsewhere has shown that live bird markets (LBMs) play a significant role in the ecology and zoonotic transmission of avian influenzas (AIs) including H5N1 and H7N9. Vietnam has a large number of LBMs reflecting the consumer preferences for live poultry. Under pressure to mitigate risks for H7N9 and other zoonotic AIs, Vietnam is considering, among other mitigation measures, temporary closures of LBMs as a policy to reduce risk of AI outbreaks. However, the efficacy of market closure is debated, particularly because little is known about how poultry traders may react, and whether trading may emerge outside formal marketplaces. Combining efforts of anthropologists, economists, sociologists, and veterinarians can be useful to elucidate the drivers behind poultry traders' reactions and better understanding the barriers to implementing risk mitigation measures. In this paper, we present results from a stakeholder survey of LBM stakeholders in Vietnam. Our qualitative data show that trading outside formal markets is very likely to occur in the event of a temporary LBM market closure. Our data show that the poultry value chain in Vietnam remains highly flexible, with traders willing and able to trade poultry in many possible locations. Our results indicate that simplification of the poultry value chain along with strict enforcement, engagement of stakeholders, and adequate communication would be a necessary prerequisite before market closure could be an effective policy.

Keywords: avian influenza, live bird market, market closure, trader opinion, poultry value chain, risk mitigation

INTRODUCTION AND PURPOSE

A number of studies point to the significance of live bird markets (LBMs) in the maintenance, transmission, and spread of avian influenza (AI) viruses in poultry populations, and highlight the role of LBMs in transmission of zoonotic influenza viruses to human populations (1–7). Studies in Vietnam have shown that LBMs are at high risk for presence of AI viruses (8), and market practices were significantly associated with AI virus contamination (9–11). In China, epidemiological studies have indicated that exposure to live poultry or contaminated environments, especially markets where live birds are sold, were significant risk factors for influenza A (H7N9) infection in human (6, 12). In a number of Chinese cities, government authorities have closed live poultry markets as part of the effort to control the epidemic.[1]

Emerging subtypes or clades of highly pathogenic avian influenza (HPAI) viruses could be detected in Vietnam months or years after similar viruses were detected in China, e.g., H5N1 clade 1 and clade 2.3.2.1a and H5N6. Cross-border trade in poultry is suspected to be an important mechanism for the introduction of new zoonotic and HPAI viruses into Vietnam (14). The government of Vietnam is considering closure of LBMs as a possible emergency intervention if H7N9 or other zoonotic influenza viruses are detected in the market or in a person who has visited the market. Besides reducing direct contact between poultry and people, temporary market closure would enable cleaning and disinfection aimed at reducing virus accumulation, amplification, and spread among poultry population and transmit to humans. Market closure would include culling and disposal of all poultry on the day of closure, and the prohibition of holding or selling poultry in the market for 7 days while cleaning and disinfection would be conducted [Vietnam Ministry of Agriculture and Rural Development Action Plan (2014) on Emergency Response to Dangerous Avian Influenza Virus Strains with Potential Infection on Humans].

Although scientific consensus exists about the role of LBMs in the ecology of AI, significant debate remains about whether closure of LBMs will effectively transform this viral ecology and reduce risk of AI transmission. Both qualitative and quantitative studies of China's 2013 LBM closures suggested that they were effective in reducing the number of human infections with H7N9 (15–16). Studies in Hong Kong, in particular, have shown that emergency closure can transform the ecology of AI and reduce risk of transmission (17, 18). However, Fournié and Pfeiffer (19) question whether market closure can be an effective long-term strategy or can be utilized in resource-poor settings. In particular, they suggest that closure may not be as effective in a future epidemic if informal marketing channels develop. Parallel informal trade routes could spread the virus to new locations, transform the structure of viral transmission networks, and worst of all, render existing targeted surveillance and risk management activities less effective (13). Fournié and Pfeiffer (19) highlight the importance of assessing the feasibility of closing markets and the likelihood of unintended adverse results, before implementing such a measure.

Although previous studies analyzed the natural ecology of poultry and AI viruses in LBMs, they left unanswered this fundamental question about the feasibility of market interventions: how will poultry traders and LBM market managers respond to market interventions, including temporary market closure? This study aims to answer this question through a qualitative, participatory survey of the perceptions and opinions of LBM stakeholders toward disease risk in LBMs and toward temporary market closure as part of government risk mitigation interventions.

Previous surveys in LBMs focused on hygiene practices and risk behaviors (20), quantifying trader scale, and analyzing market chains (9, 11, 21), but provided minimal information about the perceptions and motivations of traders or market managers. To date, a few studies have analyzed social and cultural factors impacting the ecology of AI, focusing on farmers (22, 23) or consumers (24). This study fills this remaining gap in the understanding of social and cultural factors that are relevant for the ecological dynamics of AI through an in-depth survey of the perceptions and opinions of poultry traders and market managers in LBMs, with a particular focus on their perceptions toward temporary market closures. The aim of this study is to provide policy makers with field evidence for developing adequate risk mitigation policies in response to new introductions or detection of zoonotic AI viruses.

METHODOLOGY

Prospective Participatory Stakeholder Research

The study employed a participatory stakeholder approach that investigates perceptions and opinions of stakeholders about problems and policies (25). Participatory research can be defined as "systematic inquiry, with the collaboration of those affected by the issue being studied, for the purposes of education and taking action or effecting change" (26). Previous research has shown that early stakeholder involvement in the response to an environment or health problem is more effective in terms of reducing negative impact and adverse reactions than *post hoc* surveys of stakeholder reactions to a policy intervention (25, 27). In this study, we adopted a prospective approach by surveying the opinions and perceptions of stakeholders in advance of policy implementation.

The study was designed by an interdisciplinary team of trained anthropologists and sociologists, including both Vietnamese and international researchers, and in consultation with experts in animal health and AI. Guiding questions were prepared and pretested in one of the LBMs in Ha Noi, which are similar in structure and trading operations with LBMs in survey areas. The piloting markets were excluded from the survey. The interviews conducted by a team of three researchers with in-depth experience in participatory survey methods. The interviewers exchanged information at the end of each interview day in the field to ensure consistency of the field interviews. Questions were addressing aspects related to market closures such as reaction of stakeholders, impact of market closure on the livelihoods, other trading options for poultry in case of market closure, reaction on compulsory culling of poultry, and willingness of stakeholders to collaborate and under which conditions traders would

[1] The strategy of live bird market closure is based in part on the earlier experiences of Hong Kong. The 1997 outbreak of H5N1 in Hong Kong continues to provide a standing example of the potential for reduction or even eradication of avian influenza viruses through closure of markets coupled with poultry culls. However, as the Hong Kong case also demonstrates, the ability to eradicate AI from one city or region does not ensure protection against the later reintroduction of the virus (13).

comply with government policy on market closure. Interviews were conducted from February to March 2014. In total, 91 face-to-face interviews were conducted with poultry wholesalers, middlemen, transporters, and retailers. The interviewees were selected randomly in the survey markets. Notes were taken by the interviewers, and data were subsequently analyzed by coding of interviews. Interviews were also conducted with market management boards in six of eight LBMs. Two markets did not have market management boards, as they were open street markets.

During interviews, stakeholders were presented with the possibility that markets would be closed by the government for a temporary period of time, either 7 or 21 days, based on the Vietnam action plan on emergency response to dangerous AI virus strains with potential infection on humans. Under this plan, the decision between 7 and 21 days closure should be based on the magnitude of the disease situation. While a closure of 7 days would apply as emergency control response in markets in a small geographic area, a 21-day closure would come into force in case of geographic spread of the disease and would include markets in a wider geographic area. These stakeholder groups were defined as follows: (1) a *market manager* appointed by local government to manage the market; (2) a *wholesaler* trades a *high* volume of poultry, primarily purchasing from farms and selling to other traders; (3) a *middleman* trades a *small to medium* volume of poultry, purchased from wholesalers and sold to other traders; (4) a *retailer* trades a *small* volume of poultry and sells directly to the end user (consumer); and (5) a *consumer* is a purchaser and end user of poultry.

Research Setting: The LBMs

Interviews were conducted in eight LBMs in four provinces: Ha Vi and Bac Thang Long markets (Ha Noi), Re Market (Hai Phong), Dam Chieu (Hai Phong), Tuc Duyen (Thai Nguyen), Ba Hang (Thai Nguyen), Gieng Vuong (Lang Son), and That Khe (Lang Son). The markets were selected to represent diversity in scale, management, trading operations, and mode of construction, which would need to be considered by government interventions in case of HPAI outbreaks.

The term "traders" (**Table 1**) includes live poultry wholesalers, middlemen, and retailers. The number of live poultry traders in each market range from 10 to 190, with a mean of 62 and a median of 57. The largest market is Ha Vi market, with 190 wholesalers and middlemen trading over 30,000 birds per day.

All the surveyed markets operate 7 days per week. Three out of the eight markets are sheltered or roofed and enclosed. Traders with permanent stalls in the market pay a monthly hygiene fee of about 50,000 VND[2] to the market management board, which hires cleaners to clean the market at the end of each day. In addition, investments have been made in two of these markets to improve the hygienic situation. For example, Ha Vi market was built during 2007–2011 with funds from the World Bank through the Vietnam Animal and Human Influenza Control and Preparedness (VAHIP) project. The VAHIP invested in a waste water treatment and drainage system. However, in all three of these markets, drainage systems remained clogged by solid wastes and therefore ineffective.

Four of the eight markets located on open streets. In these street markets, traders pay a daily market fee of about 3,000–5,000 VND[3] per trader. Some of these street markets are nearby to official, enclosed marketplaces that do not sell live poultry. One market is neither indoors nor on a public street, but on an area of barren land. When it rains, the ground turns to mud.

[2]Equivalent to 2.2 USD.

RESULTS

In response to the possible 7-day market closure, all stakeholders pointed to the likelihood that parallel trading outside the market would emerge. At the same time, responses to parallel trading diverged according to the scale of the traders' operations. The opinion of stakeholders on market closure for 7 days is summarized in **Table 2**.

However, in response to the possible 21-day market closure, the divergence of opinions shifted. In this case, middlemen and retailers joined wholesalers in declaring that they would halt trading of live poultry altogether. They stated that with such a long, and probably widespread closure of markets, the market demand for poultry would likely decline sharply. Many traders suggested they would temporarily shift to other jobs, such as agricultural work, or trading other products (vegetables, rice, pork, kittens, puppies, etc.). In addition, they would request for exemption or reduction of taxes and other charges (market fee and charges). Market managers remained consistent in declaring they would comply with regulations, and also noted that they would request remissions of taxes or revenue charges.

Although wholesalers had declared they would halt poultry operations during both 7- and 21-day market closures, further inquiry revealed that they disagreed with compulsory culling of poultry associated with market closures in case of market closures as specified in the Vietnam action plan. Wholesalers argued that their birds have been carefully selected and have farm origin and vaccination certificates issued by animal health authorities. Therefore, they believed the birds could not be responsible for any AI outbreaks, and therefore should not be culled. If the authorities forcibly cull poultry, wholesalers argue that they should be compensated according to the purchase (farm) price or at 50–70% of the birds' market value. In addition, they called for assistance, such as preferential loans, following the end of the outbreak and

[3]Equivalent to 0.12–0.22 USD.

TABLE 1 | Number of traders in survey markets.

Market name	Location	Number of traders
Ha Vi	Ha Noi city	190
Bac Thang Long	Ha Noi city	60
Re market	Hai Phong city	13
Dam Chieu	Hai Phong city	10
Tuc Duyen	Thai Nguyen province	45
Ba Hang	Thai Nguyen province	55
Gieng Vuong	Lang Son province	67
That Khe	Lang Son province	59

TABLE 2 | Opinion of stakeholders on market closure for a duration of 7 days.

Stakeholder	Opinion	Reaction	Concern
Retailer	Would follow government regulation and would not trade poultry in the market	→ Would continue to *sell poultry at home, nearby streets or make door-to-door deliveries*	Worry that regulations do not apply equally to all retailers leading to business disadvantages
Middlemen	Would follow government regulation	→ Would collect poultry from other markets or directly from farms and sell to other markets or other places such as street intersections	Worry about losing trading networks
Wholesaler	Would follow regulation	→ Would stop poultry trading	Worry about losing trading networks
Market manager	Insist they would follow the regulation		Worry about retailers continuing to trade live poultry outside markets and in public streets Stress that it would be necessary to have close coordination between various levels of the government to ensure strict enforcement and monitoring

the resumption of normal market activities. Middlemen and retailers also disagreed with the culling policy, in particular the culling of "healthy looking" birds. Both groups of stakeholders called on the government to compensate for any culled birds at market or farm price. Retailers also suggested that they might try to bring birds home to avoid being culled. The market managers worried that traders would protest against any culling of poultry. They suggested that any decision to cull poultry should combine strict enforcement with good communication and explanation. They noted that the government does have a mechanism for assistance and compensation in the case of poultry culls and suggested it should be used to enhance compliance of traders.

If a zoonotic influenza virus is detected in a market, the veterinary authorities will also need to go beyond local market interventions and rapidly identify the source of the infection to focus control measures at the origin. When reporting about the willingness and ability to locate the farms of origin, responses varied according to the scale and structure of trader operations. Wholesalers claimed that tracing their poultry back to the farm of origin would be easy since their poultry typically have origin and vaccination certificates issued by animal health authorities. Wholesalers would be able and willing to provide the addresses of the farms of origin.

Middlemen claimed they purchased birds both directly from farms and from other markets or street vendors. Birds purchased directly from farms would be easy to trace, but it would be difficult or impossible to trace birds purchased at markets or on roads. Finally, retailers suggested that it would be difficult or impossible to trace the origin farm of their birds, because they purchase birds from different sources.

DISCUSSION: VALUE CHAIN FLEXIBILITY AND THE ECOLOGY OF AI

Research in Vietnam indicates that markets connected through trade networks can contribute to large-scale epidemics, while providing opportunities for effective control as well. Targeting network hubs for surveillance, hygiene and biosecurity interventions at LBMs could reduce the transmission of virus through the network (11, 28) for China (4). The results of our study reveal that despite their position as hubs in trade networks, temporary "emergency" market closures of 7 days in case of new detection of AI viruses are unlikely to reduce the spread of AI viruses. Poultry traders, in particular middlemen and retailers, maintain a highly flexible practice of market transactions along the poultry value chain. The physical location of the LBM is only one among many possible transaction sites. Our results showed that temporary market closure for 7 days is likely to lead to establishment of parallel, informal, and uncontrolled live poultry trade, which could lead to virus introduction into non-affected areas (29). Our study concludes that given the structure of Vietnam's poultry value chain, which remains highly flexible with numerous middlemen between producer and consumer, closure of LBMs, unless implemented on a longer term and in a larger geographical area or nationwide, will be an ineffective strategy for reducing the risk of AI. However, decisions on longer term closures, would need to take into consideration the economic effects on the poultry sector (30). The importance of timely and appropriate compensation following simple procedures for culled birds appeared consistently among the responses of all the stakeholders. While current Vietnam government regulations do foresee financial compensation for compulsory culling of poultry at farms, there is at present no provision for compensation for poultry culled at markets. If stakeholders do not perceive culling as a justified measure, they will be more prone to disobey regulations and trade their poultry through unofficial channels. Proper communication of compensation schemes has shown to be crucial to improve compliance and avoid unintended effects (31, 32).

The results of our study demonstrated that poultry value chains in northern Vietnam contain a high degree of flexibility. In an agricultural value chain, "actors are connected along a chain producing, transforming, and bringing goods and services to end-consumers through a sequenced set of activities" (33). Value chain analysis has tended to provide formalistic accounts of market relationships, focusing on the vertical links that bring a product "from farm to fork." We propose the concept of the "flexibility" of the value chain to describe the capacity of a value chain to shift spatially, or to forge new transaction links, in the event that a particular site or relationship of exchange is eliminated (e.g., through market closure). Our study exposed the high degree of flexibility of the value chain in Vietnam. The flexibility of market transactions far exceeds the physical space of the marketplace, i.e., the LBM. If the LBM is closed for 7 days, trading would continue in other forms and locations. At the same time, this flexibility itself was not shared equally by all stakeholders. Wholesalers, due to the large scale of their operations, were more closely bound to the institutional setting and physical site of the formal LBM marketplace. Furthermore, they reported that they purchase poultry with official certification of farm of origin, indicating a relatively stable and traceable part of the value chain. Small retailers, by contrast, purchase birds from middlemen or wholesalers each day and sell them again, often on the side of small streets or by delivering them to small restaurants. Middlemen buy and sell poultry with the highest degree of flexibility: they report that they could easily shift operations to other markets in the event of market closure for 7 days. The restructuring and simplification of the poultry value chain as suggested by several poultry value chain studies conducted in Vietnam (FAO unpublished data), by reducing the number of middlemen and small-scale traders, could decrease the overall flexibility of trading and therefore improve the effectiveness of market closure. The flexibility of the poultry value chain explains why market closure may not be an effective strategy for reducing the spread of AI or AI incursion risk. The closure of the marketplace is intended to eliminate a key node in the network of AI transmission. But LBM traders do not necessarily confine their trading to the LBM. As traders exploit the flexibility of the value chain and shift transactions to parallel trading sites, live poultry trading networks may expand and fragment, increasing rather than reducing AI transmission and risk.

Finally, our results also revealed important limits to the flexibility of the poultry value chain. A minor limit exists in the length of market closure. During a 7-day closure, all stakeholders described how they would adapt by shifting market operations to other locations, but during closure of minimum 21 days, all stakeholders reported that they would halt trading operations. Rather than trading live poultry in alternate locations along the value chain, they reported that they would shift to other forms of economic activity: trading non-poultry products or even returning to farm work. However, prolonged market closures may result in high economic losses and impact livelihoods in the poultry production sector (34).

CONCLUSION

The present study shows that analyzing perceptions of stakeholders regarding risk mitigation interventions, such as the temporary closures of markets, are crucial for the design of effective policies and to avoid adverse results.

To date, the implementation of market closures has been based on viral surveillance data relying on virus detection alone. Neglecting the fact that LBMs are human, social and cultural institutions may render disease control policy ineffective. In fact, the role of LBMs in the chain of influenza transmission is conditioned by the practices and perceptions of LBM stakeholders. As a result, although market places may be closed, marketing practices and networks may continue to operate in a shifted form and facilitate AI virus spread. The position of LBMs in the poultry value chain in the North of Vietnam exemplify how the natural ecology of AI is shaped as a consequence of human perceptions and reflexive practices (35). In such cases, understanding the ecology of the virus and how to manage its risks relies on understanding the human stakeholders that construct, and can unexpectedly reconstruct, the links in the chains of viral transmission.

Stakeholder participation should be an integral part of the development of science-based policy interventions, not only for reasons of equity and ownership but also more importantly to provide accurate knowledge about natural ecology itself (25) and to ensure planning and implementation of more effective risk mitigation measures.

ETHICS STATEMENT

The study was considered low risk as the main risks to study respondents were believed to be abreact of confidentiality and privacy. To mitigate these risks, the following safeguards were put in place. Verbal informed consent was received from study participants during the recruitment process. Another verbal informed consent was received from participants before each interview or group discussion after clear explanation about the objectives and content of the study. Each study participant was assigned a code to maintain confidentiality during data collection and analysis. No personal identifiers, including names, were collected at any time throughout the study.

AUTHOR CONTRIBUTIONS

All the authors: substantial contributions to the design of the study, collecting data in the field, and analysis and interpretation of the data; drafting the report; approval of the version to be published; and agreement to be accountable for all aspects of the manuscript.

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Market Impact of Foot-and-Mouth Disease Control Strategies: A UK Case Study

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Foot-and-mouth disease (FMD) poses a serious threat to the agricultural sector due to its highly contagious nature. Outbreaks of FMD can lead to substantial disruptions to livestock markets due to loss of production and access to international markets. In a previously FMD-free country, the use of vaccination to augment control of an FMD outbreak is increasingly being recognized as an alternative control strategy to direct slaughtering [stamping-out (SO)]. The choice of control strategy has implications on production, trade, and hence prices of the sector. Specific choice of eradication strategies depends on their costs and benefits. Economic impact assessments are often based on benefit–cost framework, which provide detailed information on the changes in profit for a farm or budget implications for a government (1). However, this framework cannot capture price effects caused by changes in production due to culling of animals; access to international markets; and consumers' reaction. These three impacts combine to affect equilibrium within commodity markets (2). This paper provides assessment of sectoral level impacts of the eradication choices of FMD outbreaks, which are typically not available from benefit–cost framework, in the context of the UK. The FAPRI-UK model, a partial equilibrium model of the agricultural sector, is utilized to investigate market outcomes of different control strategies (namely SO and vaccinate-to-die) in the case of FMD outbreaks. The outputs from the simulations of the EXODIS epidemiological model (number of animals culled/vaccinated and duration of outbreak) are used as inputs within the economic model to capture the overall price impact of the animal destruction, export ban, and consumers' response.

Keywords: foot-and-mouth disease, partial equilibrium model, disease control strategy, market impact, economics

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INTRODUCTION

Foot-and-mouth disease (FMD) poses a serious threat to the agricultural sector due to its highly contagious nature, which can lead to substantial disruptions to livestock markets. It is estimated that the outbreak in the UK in 2001 resulted in losses to agriculture and the food chain of approximately £3.1 billion, with further significant impacts on the wider economy (3). A *stamping-out (SO)* policy was implemented in 2001 to control the disease, whereby all infected stock and others exposed to infection (dangerous contact herds) were culled. Subsequent legislation included provisions for emergency vaccination as a control strategy. Vaccination was considered as an alternative control strategy during the 2007 outbreak, but ultimately was not deployed due to advice on the degree of risk of the disease spreading (4). There are two main vaccination strategies: *vaccinate-to-die (V-t-D)* and *vaccinate-to-live*. Under the *V-t-D* strategy, vaccinated animals are culled. Compared to the *SO* strategy, this may entail higher compensation spending, but shorten the duration of the outbreak by slowing the spread of the disease. Under the alternative *vaccinate-to-live* strategy, vaccinated animals remain in the population and may be slaughtered commercially, but this strategy entails delays in the reopening of international markets.

The market implications will vary across different control strategies due to, for example, differences in the duration of the outbreak, number of animals culled and closure of export markets. It is not straightforward to discern the market impact from previous outbreaks due to evolvement of contingency plans, country variations, dependency on export markets, other shocks to the market, etc. For example, when Argentina used vaccination to eradicate FMD in the early 2000s, the economy experienced severe downturns during this period, making it difficult to isolate the market impacts of the control strategy. FMD outbreaks are rare in countries, such as the UK, but will potentially have serious consequences if it occurs. It is, therefore, important to gain insights on disease management from not only historic experiences but also modeling exercises, which are built based on the logical abstraction of reality.

This paper investigates the market impacts of the strategies of *SO* versus *V-t-D* in FMD control in the case of the UK using a partial equilibrium modeling framework. The results are based on linking the FAPRI-UK partial equilibrium model and the EXODIS epidemiological model. Outputs from the simulations of the EXODIS model (number of animals culled/vaccinated and duration of outbreak) are used as inputs within the FAPRI-UK model to capture the price impact of the destruction of animals and restrictions to internal trade. The EXODIS model is stochastic, that is, the same virus can potentially result in a small- or a large-scale outbreak. Within this paper, market impacts are assessed for different scales of a potential outbreak. We begin with a review of the literature in Section "Literature Review." This is followed by descriptions of the economic partial equilibrium model, the FAPRI-UK model and alternative scenarios in Section "Model and Scenarios." The results are presented in Section "Results" and conclusions are drawn in Section "Summary and Discussion."

LITERATURE REVIEW

Due to the potential loss caused by FMD outbreaks, control strategies are constantly reviewed and evaluated, among which economic assessments are important. Economic assessments mostly concern the costs of alternative control strategies and/or value of certain responses, such as early detection, which help to reduce costs [e.g., Ref. (5, 6)]. These analyses are often based on the benefit–cost framework, which provide detailed information on the changes in profit for a farm or budget implications for a government (1). However, the benefit–cost framework cannot capture market price effects caused by changes in the following:

- Production due to culling of animals;
- Access to international markets; and
- Consumers' reaction.

These three impacts combine to affect equilibrium within commodity markets (2). Reduced production as a result of the destruction of animals exerts a positive impact on price. Counteracting this, if exports are banned in response to the outbreak, additional production must be absorbed within the domestic market leading to an increase in supply. In addition, although FMD does not typically affect humans, there may be a negative consumption response to an outbreak due to consumer health concerns, even if these concerns are unfounded. Such concerns would lead to an inward shift in the demand curve and exert a downward impact on price. The ultimate impact on price depends on the weight of these individual effects and will vary across sectors depending on, for example, the importance of exports relative to domestic consumption. The partial equilibrium modeling framework models both the supply side and the demand side of a market and solves for a market clearance price. Thus, it is better suited to capture these effects. It enhances understanding of the market consequences for different commodities of different control strategies in response to an outbreak, complementing the benefit–cost analysis. There are assessments of FMD outbreaks and/or FMD control strategies using partial equilibrium models for the United States (7–10), Australia (11), Canada (12), and Mexico (13).

The economic impacts of vaccination as a control strategy are explicitly examined by Hagerman et al. (8), Schroeder et al. (9), Buetre et al. (11) and Tozer et al. (12), which reflect the rising recognition of this strategy in recent years. Both Hagerman et al. (8) and Buetre et al. (11) find that the desirability of vaccination depends on the scale of the outbreak. The cost of vaccination strategy cannot be justified when the outbreak is small. Also in the context of the US, Schroeder et al. (9) examines outbreaks at a larger scale compared to those in Hagerman et al. (8) and finds substantial benefits of using the vaccination strategy. Tozer et al. (12) is less informative in control strategy choices as it focuses on the dynamics of producer decisions using a discrete time optimal control model. The model assumes deterministic parameters that characterize the way in which FMD develops; in other words, there is no uncertainty with regard to the spread of the disease itself. To our knowledge, the market impacts of vaccination strategy for FMD control have not been examined in the UK. Following Hagerman et al. (8) and Buetre et al. (11), the control strategies will be assessed for potential outbreaks of different scales.

MODEL AND SCENARIOS

Model

The FAPRI-UK model is an annual partial equilibrium model of the agricultural sector of the UK. Commodities modeled include wheat, barley, rapeseed, oats, beef, lamb, pork, poultry, dairy, and biofuel. Final demand for the meats and dairy entail derived demand for animals for slaughter and dairy cows and derived demand for feed from the crop sector. The dynamics in breeding herd building and livestock production are captured through appropriate lags in the equations. Production of these commodities is modeled at the level of the four countries of the

UK: England, Wales, Scotland, and Northern Ireland. Demand is modeled at the UK level. Under most analyses, the model is run in conjunction with the EU-GOLD model so that markets clear at the EU level as markets of the Member States within the EU are deeply integrated.[1,2] This means that international trade, excess supply, and demand at the UK level feed into the EU for solving the equilibrium prices.

The FAPRI-UK modeling system produces Baseline projections over a 10-year period of key variables in the beef, sheep, pig, poultry, dairy, and crop sectors for each country in the UK under the assumption that current policies remain in place and specific macroeconomic assumptions hold. The Baseline provides a benchmark against which projections of the policy scenarios can be compared and interpreted (14).[3] The Baseline used in this analysis was finalized in Spring 2016 and covers the projection period 2016–2025.

When an FMD outbreak occurs, export of animal products from the outbreak country will be banned until the disease is eradicated and a specified waiting period has passed. During this period, the UK markets will be temporarily disintegrated from the EU. New equations for import and export of beef, lamb, and pork are developed so that these markets clear at the UK level. Then the export ban is incorporated as a shock to the export equation. The size of the shock depends on the duration of the disease outbreak and the waiting period. The time taken to eradicating the disease obviously depends on the success of the control strategy used, while the waiting period also depends on the control strategy as specified in existing regulations. Details of the waiting period for each of the control strategies examined within this paper and the specification of the size of the shock to export are provided in the next section.

In addition, the FMD outbreak will cause a shock to the production of the meat and dairy products as infected (and perhaps vaccinated livestock) are culled. Given the biological dynamics in livestock sector, culled livestock have impacts on meat production beyond the outbreak year, particularly in the beef sector. In general, if commodities redirected from export outweigh the reduction in production following an FMD outbreak, this results in excess supply, which exerts a downward impact on price in the domestic market. Price falls may deepen, depending on whether the outbreak causes a food scare in consumption.[4]

The last route through which equilibrium is restored is import adjustment. Imports will reduce in response to lower prices in the UK as exports being redirected to the domestic market. Nevertheless, domestic prices would rarely be higher than EU prices during the year of outbreak as imports are always possible. For the markets to reach equilibrium following an FMD outbreak, the price elasticity of import is a particularly crucial parameter; that is, the extent of import changes relative to price change. It is important to acknowledge that there is considerable uncertainty regarding the extent to which imports are likely to be displaced by the rechanneling of exports to the domestic market. The rate of displacement is of particular concern as the export ban implies a sudden substantial increase in supply to the domestic market from the rechanneled exports. This has important implications on the price impact of an FMD outbreak. Imports may be slow to readjust due to contractual reasons and demand requirements, e.g., imports from the southern hemisphere may fulfill demand requirements during specific periods of the season. It is also possible that imports adjust quickly in response to the rechanneling of exports. As a result, sensitivity analyses regarding import adjustments are carried out in which changes in imports are exogenously imposed. Two extreme cases are examined: no displacement and substantial displacement. In the case of no displacement, it is assumed that imports remain unchanged compared to Baseline projections. This reflects the assumption that imports are slow to adjust and cannot be readily canceled. In the case of substantial displacement, it is assumed that imports are reduced by 90% of exports that are diverted to the domestic market due to the export ban, implying that imports adjust instantaneously in response to the imposition of an export ban. The sensitivity analysis provides a means to quantify the price impact of an FMD outbreak under different trade assumptions.

Scenarios

Two FMD control strategies are examined in this paper.

Stamping-Out

Under this scenario, numbers of animals culled from simulations of the epidemiological model are incorporated within the economic model, resulting in reductions in livestock numbers and animals available for slaughter. In addition to the number of culled animals, the epidemiological model provides data on the duration of the outbreak. Under the "SO" scenario, the waiting period for applying for disease-free status and resuming export is 90 days after the last case of FMD.

Vaccinate-to-Die

Similar to scenario (i), numbers of culled animals from the epidemiological model are entered as supply shocks in the economic model and exports resume 90 days after the last infected and vaccinated animals are culled.

The analysis undertaken in this paper is based on stochastic simulations of the EXODIS epidemiological model undertaken by the Animal and Plant Health Agency as an extension of Exercise Rowan.[5] The epidemiological model simulations are based on an outbreak equivalent to the characteristics of the

[1] The EU-GOLD model is a partial equilibrium model of the agricultural sector at the EU level. It is developed and maintained by the Food and Agricultural Policy Research Institute (FAPRI) at the University of Missouri.

[2] This study was carried out before the UK referendum of exiting the EU.

[3] Project information on the AFBI website: https://www.afbini.gov.uk/analysis-agricultural-commodity-markets-fapri-uk-project.

[4] Note the analysis in this paper focuses on the effect of shock to production and exports. We do not examine the implication of a shock in consumption as it is difficult to discern the size of such a shock from real data as the scale of the shock in the simulations is smaller than the 2001 outbreak.

[5] The initial phase of Exercise Rowan was undertaken in the latter part of 2015. During the exercise, the EXODIS model was used to test FMD response capability in the UK. See Roche et al. (15) for further information on the EXODIS model.

virus in the UK in 2001, but take into account up-to-date UK contingency plans. The stochastic output from the epidemiological model yielded 200 outcomes, which reflect alternative developments of the same FMD virus. In order to identify the market impact of these different outcomes, the median outputs from the epidemiological model are used as inputs within the economic model. In addition, we consider the tails of the distribution from the epidemiological model outcomes. In particular, the 95th percentile is used to represent the situation in which the virus develops into a particularly serious outbreak, as reflected in the number of livestock affected and the duration of the disease outbreak. The 5th percentile replicates a mild outbreak. As shown in the summary statistics in **Table 1**, the number of culled animals is higher under the V-t-D simulations compared to SO. However, the duration of the disease-free status period is lower under the former, particularly with regard to the 95th percentile. A matching procedure was used to identify individual simulations that approximate the median, 5th and 95th percentile statistics of all the relevant variables (numbers of livestock culled of different species and duration of disease outbreak).[6]

Animals culled under the *SO* scenario in the simulated outbreak of median scale (based on the epidemiological model) represent 1.8, 0.6, and 0.2% of the projected total number slaughtered of the year for the beef, sheep, and pig sector, respectively. The percentages rise to 4.8, 1.9, and 0.7% in the *V-t-D* scenario. However, it should be noted that while the breeding herd and animals at different life stages are not distinguished in the epidemiological model, they are modeled separately in the economic model. Therefore, total number culled by species are proportioned to the breeding herd and animal for meat purpose at different life stages based on historic census before they are incorporated into the economic model. This implies that the percentages mentioned earlier are greater than the production shock to the year of the outbreak while the culling will exert some effects for the year(s) following the outbreak.

[6]Rather than devising a rule to disaggregate UK epidemiology outputs at the regional level, individual simulations that approximate the median, 5th and 95th percentile statistics of all the relevant variables (numbers of livestock culled of different species and duration of disease outbreak) at the UK-level were identified. It is relatively straightforward to identify individual simulations that closely approximate the 5th percentile and median, but less so for the 95th percentile of all the sectors simultaneously. With regard to individual simulations, some sectors are not affected to the same extent compared to the statistics for the 95th percentile. More emphasis was placed on the beef and sheep sectors within the matching procedure. The relevant variables from the chosen individual simulations closely match the 95th statistics for these sectors, but slightly lower outcomes emerged for the pig sector. Nevertheless, the differences were sufficiently small such that qualitative differences between the scenarios for all the sectors, including the pig, still hold.

TABLE 1 | Summary statistics from EXODIS epidemiology model.

		Stamping-out	Vaccinate-to-die
Infected premises	Median	230	120
	5 Percentile	134	75
	95 Percentile	360	181
Period to apply for disease-free status (days)	Median	171	141
	5 Percentile	152	129
	95 Percentile	224	176
Total culled animals	Median	342,558	1,020,682
	5 Percentile	191,310	636,701
	95 Percentile	593,892	1,444,701
Total vaccinated animals	Median	–	837,518
	5 Percentile	–	529,050
	95 Percentile	–	1,174,954

The FMD outbreak in the UK in 2001 lasted for 221 days and the number of animals culled was over 4 million. By contrast, the 2007 outbreak lasted for 58 days and only 2,160 animals were culled (4). It appears that the 2001 outbreak is more serious than the case of 95th percentile presented in this study (**Table 1**). Although the epidemiological simulations are based on an outbreak equivalent to the characteristics of the virus in the UK in 2001, direct comparison is difficult because the model simulations take into account the up-to-date UK contingency plans, which have been significantly reviewed and updated following the outbreaks.

Underlying the *SO* and *V-t-D* scenarios, it is assumed that all exports of beef, sheep, and pig meat are halted for the duration of the outbreak plus 3 months after the detection of the last case, in line with World Animal Health Guidelines. Thus, it is assumed that there is no regionalization, i.e., exports from the whole country are banned. The reduction in exports as a result of the export ban is computed as a proportion of the length of the export ban:

$$\text{Export Reduction} = \text{Export under the Baseline} \times (\text{Days of Export Ban}/365).$$

The length of the export ban is defined as the period of the last reported case plus the waiting period before it is possible to apply for disease-free status. This definition may be interpreted as the most optimistic estimation of the duration of the export ban as it implies no delay in approval. In the past two FMD outbreaks in the UK (2001 and 2007), both outbreaks ended in around September of the year and the UK regained disease-free status in the beginning of the following year. This suggests that the waiting period in these two cases were not much longer than the minimum required (i.e., 3 months). However, it should be noted that in both cases, the UK used the *SO* strategy only. A summary of the scenarios (including sensitivity analysis of import adjustments) is presented in **Table 2**.

RESULTS

Impact during the Year of Outbreak

Table 3 reports the impacts of the SO and V-t-D strategies for outbreaks of difference scales with various assumptions on import adjustment during the year of outbreak.

Starting with the "*SO—endogenous displacement*" scenario, UK prices fall by 7.9, 24.7 and 17.3%, respectively, in the beef, sheep, and pig sectors in 2017 for an outbreak of median scale. The negative price impact is attributable to the additional production absorbed onto the domestic market due to the export ban, which leads to an increase in domestic supply. The limited decline in production is insufficient to offset the rechanneling of

TABLE 2 | Foot-and-mouth disease (FMD) control scenarios.

FMD control strategies	Percentiles	Export ban period (days)	Trade assumptions		
Stamping-Out	5th	152	*Endogenous displacement*	*No displacement*	*Substantial displacement*
Export ban = disease	50th (median)	171	Imports are partially displaced by	Imports remain	Imports reduced by 90% of
period + 90 days	95th	224	absorption of exports on the	unchanged	exports that are absorbed on
Vaccinate-to-die	5th	129	domestic market depending on		the domestic market
Export ban = disease	50th (median)	141	changes in relative price		
period + 90 days	95th	176			

exports and, hence, commodity prices decline. The sheepmeat sector experiences the greatest price decline due to the high level of self-sufficiency. The projected value of output in the sheepmeat sector falls by 25.1% and primarily reflects the drop in price.

Compared to the median, the negative price impact is greater following a more serious outbreak (the 95th percentile version of the scenario). The prices of beef, sheep meat, and pig meat fall by 9.3, 31.4, and 22.2%, respectively. Despite the more serious nature of the outbreak, the prices are lower under the 95th simulations compared the median. The negative production impact from the larger number of animals culled is more than offset by the longer duration of the outbreak, which results in an extended export ban and more produce being absorbed on the domestic market. By contrast, the milder outbreak experienced under the 5th percentile version of the scenario results in smaller price impacts compared to the median.

Under the "*endogenous displacement*" simulations the absorption of exports onto the domestic market is partially counteracted by a fall in imports. When it is assumed that imports do not adjust to the export ban ("no displacement" scenario), price drops are more severe. In the case of the median outbreak, beef, sheep meat, and pig meat prices fall by 11.2, 43.2, and 22.1%, respectively. Within this scenario, the absorption of exports onto the domestic market is not counteracted by a fall in imports, leading to a greater negative supply shock. While this "*no displacement*" scenario is extreme it sheds light on situations in which imports adjust slowly to an export ban. It thereby provides an indication of the implications of this assumption.

The price impact is significantly less marked when imports almost fully readjust in response to the rechanneling of exports. Under the median version of the "*SO—substantial displacement*" in which it is assumed that imports are reduced by 90% of exports, the sheepmeat price is 4.4% lower than the Baseline. This contrasts with 43.2% in the no displacement scenario.

Compared to "*SO*", "*V-t-D*" leads to the culling of more animals and, hence, lower production. In addition, the "*V-t-D*" control strategy also significantly curtails the time-span of the outbreak and, as a consequence, the duration of the export ban. As a result, fewer exports are absorbed onto the domestic market. As a consequence of both these effects, the price impacts are less marked under the "*V-t-D*" scenarios compared to "*SO*." For example, the sheep meat price falls by 18.6% under the median "*V-t-D—endogenous displacement*" scenario, compared to 24.7% under the equivalent "*SO—endogenous displacement*" scenario. The projected value of output falls by a greater amount than price in percentage terms (20.2 versus 18.6%) due to the fall in production.

Comparing the results of the outbreaks at the same quantile under the *V-t-D* and *SO* scenarios, it is apparent that the projected price and value of output differences between these strategies are more marked for severe outbreaks. With regard to the sheepmeat price the difference between the two control strategies under the 95th percentile versions of these scenarios is 9.3% as the price fall under *V-t-D* is 22.1 and 31.4% under SO. This compares to 6.1% under the median. This result supports the hypothesis that the benefits of vaccination are clearer for more severe outbreaks.

Similar to the "*SO*" results, the price impacts are significantly greater when it is assumed that imports remain unchanged compared to the endogenous versions of the scenario, which entail partial adjustments in imports. For example, under the median version of the "*V-t-D—no displacement*" scenario, the sheepmeat price falls by 35%. Again, the benefits of vaccination are greater under the 95th percentile compared to the median.

In general, across the scenarios the longer the duration of the export ban the greater the price fall (**Figure 1**). One exception is the "*V-t-D*" 95th percentile scenario. Under the "*V-t-D*" 95th percentile scenario, the export ban is 176 days, compared to 171 under the "*SO*" median scenario. Despite this, the price decline is less marked under the former. The number of livestock culled under the "*V-t-D*" 95th percentile is greater than the "SO" median case and, consequently, the rechanneling of exports to the domestic market leads to smaller excess supply.

Impact over the Whole Projection Period

While commodity prices in the livestock sector are negatively affected by an FMD outbreak, this impact generally lasts for less than a year even under a serious outbreak (the longest among all the scenarios is 224 days in the case of the 95% percentile under the SO strategy). An outbreak will result in a smaller herd for the following year; breeding herd and animals for meat production numbers are smaller. To rebuild the breeding herd, some animals that would have been designated for meat production will be kept for breeding instead. As a result, meat production will be lower and prices will be higher compared to the Baseline. Among the three sectors, the restocking process is the longest for the beef sector and, therefore, beef price is the slowest to return to baseline level (**Figure 2**).[7] Beef prices do not return to the

[7]Note: the intertemporal results discussed in this section draw on the main analysis, i.e., the "Endogenous Displacement" scenario.

TABLE 3 | Foot-and-mouth disease control strategy results—comparison between baseline projections and scenario in year of outbreak (2017).

	Baseline	Endogenous displacement						No displacement						Substantial displacement					
		Stamping-out			Vaccinate-to-die			Stamping-out			Vaccinate-to-die			Stamping-out			Vaccinate-to-die		
		5th	Median	95th	5th	Median	95th	5th	Median	95th	5th	Median	95th	5th	Median	95th	5th	Median	95th
Beef sector																			
Production (1,000 t)	906	904	903	897	901	898	895	904	903	897	901	898	895	904	903	897	901	898	895
Consumption (1,000 t)	1,107	1,139	1,143	1,151	1,132	1,133	1,138	1,159	1,165	1,178	1,147	1,149	1,158	1,111	1,110	1,106	1,106	1,104	1,102
Net exports (1,000 t)	−201	−235	−240	−254	−231	−235	−243	−255	−262	−281	−247	−251	−263	−206	−207	−209	−205	−206	−207
Price (£/100 kg dw)	318	295	293	288	300	300	296	285	282	276	293	292	286	316	317	322	320	321	322
Output (£ million)	2,881	2,668	2,645	2,587	2,705	2,691	2,648	2,581	2,549	2,481	2,639	2,620	2,561	2,857	2,858	2,885	2,878	2,880	2,881
Changes in percent																			
Production		−0.2%	−0.3%	−0.9%	−0.6%	−0.9%	−1.2%	−0.2%	−0.3%	−0.9%	−0.6%	−0.9%	−1.2%	−0.2%	−0.3%	−0.9%	−0.6%	−0.9%	−1.2%
Consumption		2.9%	3.2%	4.0%	2.2%	2.3%	2.9%	4.7%	5.2%	6.4%	3.7%	3.8%	4.7%	0.3%	0.3%	−0.1%	−0.1%	−0.2%	−0.4%
Price		−7.2%	−7.9%	−9.3%	−5.5%	−5.8%	−7.0%	−10.2%	−11.2%	−13.1%	−7.8%	−8.3%	−10.0%	−0.6%	−0.4%	1.1%	0.5%	0.8%	1.3%
Output		−7.4%	−8.2%	−10.2%	−6.1%	−6.6%	−8.1%	−10.4%	−11.5%	−13.9%	−8.4%	−9.0%	−11.1%	−0.8%	−0.8%	0.2%	−0.1%	0.0%	0.0%
Sheep sector																			
Production (1,000 t)	319	319	318	316	316	313	310	319	318	316	316	313	310	319	318	316	316	313	310
Consumption (1,000 t)	313	338	341	350	332	333	337	364	369	386	353	355	363	317	317	318	314	312	309
Net exports (1,000 t)	7	−19	−23	−33	−16	−19	−27	−45	−52	−70	−37	−41	−53	1	1	−1	2	2	1
Price (£/100 kg dw)	375	291	283	257	307	306	292	224	213	182	247	244	225	358	359	354	370	380	389
Output (£ million)	1,199	927	898	815	971	957	906	715	677	577	782	766	698	1,140	1,140	1,121	1,170	1,192	1,207
Changes in percent																			
Production		−0.3%	−0.6%	−1.0%	−1.1%	−1.9%	−3.0%	−0.3%	−0.6%	−1.0%	−1.1%	−1.9%	−3.0%	−0.3%	−0.6%	−1.0%	−1.1%	−1.9%	−3.0%
Consumption		7.9%	8.8%	11.8%	6.1%	6.3%	7.7%	16.3%	18.0%	23.4%	12.9%	13.4%	16.1%	1.4%	1.3%	1.5%	0.3%	−0.4%	−1.1%
Price		−22.5%	−24.7%	−31.4%	−18.1%	−18.6%	−22.1%	−40.2%	−43.2%	−51.4%	−34.1%	−34.9%	−40.0%	−4.7%	−4.4%	−5.6%	−1.3%	1.3%	3.7%
Output		−22.7%	−25.1%	−32.1%	−19.0%	−20.2%	−24.4%	−40.4%	−43.5%	−51.9%	−34.8%	−36.1%	−41.8%	−4.9%	−4.9%	−6.5%	−2.4%	−0.6%	0.6%
Pig sector																			
Production (1,000 t)	916	911	910	908	909	905	902	910	909	907	908	905	901	913	913	912	911	908	905
Consumption (1,000 t)	1,429	1,501	1,510	1,536	1,488	1,491	1,506	1,520	1,531	1,563	1,504	1,507	1,526	1,436	1,437	1,439	1,433	1,430	1,429
Net exports (1,000 t)	−513	−590	−600	−628	−579	−586	−604	−610	−622	−656	−595	−603	−625	−523	−524	−527	−521	−522	−524
Price (£/100 kg dw)	132	112	109	103	115	114	110	106	103	95	110	109	104	130	130	129	131	132	132
Output (£ million)	1,211	1,017	995	935	1,046	1,035	996	963	936	866	999	986	940	1,186	1,183	1,172	1,194	1,198	1,197

(*Continued*)

TABLE 3 | Continued

Baseline	Endogenous displacement						No displacement						Substantial displacement					
	Stamping-out			Vaccinate-to-die			Stamping-out			Vaccinate-to-die			Stamping-out			Vaccinate-to-die		
	5th	Median	95th	5th	Median	95th	5th	Median	95th	5th	Median	95th	5th	Median	95th	5th	Median	95th
Changes in percent																		
Production	−0.6%	−0.7%	−0.9%	−0.8%	−1.2%	−1.5%	−0.7%	−0.8%	−1.0%	−0.9%	−1.3%	−1.6%	−0.4%	−0.4%	−0.5%	−0.5%	−0.9%	−1.2%
Consumption	5.0%	5.7%	7.5%	4.1%	4.3%	5.4%	6.3%	7.1%	9.4%	5.2%	5.5%	6.8%	0.5%	0.5%	0.7%	0.2%	0.0%	0.0%
Price	−15.5%	−17.3%	−22.2%	−12.9%	−13.5%	−16.5%	−19.9%	−22.1%	−27.8%	−16.8%	−17.6%	−21.1%	−1.7%	−2.0%	−2.8%	−0.9%	−0.1%	0.1%
Output	−16.0%	−17.9%	−22.8%	−13.6%	−14.6%	−17.8%	−20.5%	−22.7%	−28.5%	−17.6%	−18.6%	−22.4%	−2.1%	−2.3%	−3.2%	−1.4%	−1.1%	−1.2%

baseline level until the year 2023, while in the pig sector there is no discernible impact from the year 2019 onward. The paths of output values, defined as production multiplied by price, are similar to the price paths, suggesting that the increases in prices outweigh the smaller production (**Figure 2**).

To further compare the impact of the disease on the output value of the livestock sectors, output values are summed over the period of 2017–2025. All values are discounted to the 2017 value before the summation is carried out, using a discount rate of 3.5%.[8] Results are presented in **Table 4**. Over the period of 2017–2025, there are some small reductions in the total output values in the livestock sector; furthermore, the more severe the outbreak, the greater impact on total output value. Taking the longer term impact into account, the main conclusion from the previous section is still valid: the vaccination-to-die strategy helps to mitigate the market impact compared to the SO strategy.

SUMMARY AND DISCUSSION

This study is made possible following a new component developed in the partial equilibrium model that enables the UK markets to deviate from the EU. In the two most recent FMD outbreaks in the UK (very serious in 2001 versus mild in 2007), emergency vaccination was never used. The effectiveness of vaccination is shown in the experiences of other countries (for example, the Netherlands and Uruguay). The Netherlands had used emergency vaccination combined with the *V-t-D* strategy in 2001. The culling of large number of vaccinated healthy animals was not without controversy. Since then, there is ongoing exploration of the *vaccinate-to-live* strategy. However, the use of *vaccinate-to-live* strategy entails a longer export ban, which raises concerns with the industry. There could also be other issues such as logistics. Therefore, better understanding of the trade-offs of the different strategies is needed to assist decision making, which is the main purpose of our study. In a future study, we will cover the strategy of *vaccinate-to-live*.

By combining epidemiology and partial equilibrium modeling frameworks the analysis undertaken in this study demonstrates the potential market consequences of alternative FMD control strategies. It is projected that an FMD outbreak has a negative impact on market prices and value of output, regardless of the control strategy. Although the analysis is based on a virus similar to the characteristics of the 2001 outbreak, unlike this previous outbreak, the number of animals culled and, hence, the production impact is relatively modest. This reflects the evolvement of contingency plans, with co-ordination measures helping to reduce the spread of disease. While the projected decline in production under both the *SO* and *V-t-D* scenarios results in lower value of output, the largest impact on value of output stems from the drop in price due to the closure of export markets. Similarly, studies in other geographical areas have shown that the export ban exerts

[8]The choice of discount rate is based on Treasury Guidance of the UK government [the Greenbook by Treasury (16)].

FIGURE 1 | Changes in beef (upper left), sheepmeat (upper right), and pig prices (lower center) versus export ban period in the main "endogenous displacement" scenario (SO, stamping-out; V-t-D, vaccinate-to-die).

the larger impact on farm revenue compared with production changes [e.g., Ref. (2, 7)].

The more severe the disease outbreak, the greater the negative price impact, as demonstrated by comparing the median and 95% percentile versions of the scenarios. While the latter results in the culling of more animals compared to the former, which exerts an upward impact on price, this is more than offset by the market impacts of the longer duration of the export ban.

It is important to acknowledge that underlying this analysis it is assumed that exports are halted for the full duration of the outbreak plus 90 days after the last case or the last vaccinated animal is culled. The price and value of output impact would be diminished if export markets were to reopen sooner. Potentially, governments could pursue regionalization, whereby trade is allowed to resume from non-infected regions, providing it is possible to demonstrate the disease is contained (2).

In addition, the feasibility of readjusting imports is crucial. The sensitivity scenarios indicate the extent to which readjustments in imports diminish the price and revenue impacts of an FMD outbreak. If it is not possible to reduce imports swiftly the price impact could be substantial, as demonstrated under the *no displacement* scenarios. This case represents the most marked potential impact. Exporters to the UK may choose to re-channel exports to other markets if prices were to decline significantly. However, the response is unlikely to be instantaneous.

Finally, the results of this analysis indicate that the price and value of output impacts are lower under *V-t-D* compared to *SO*. This conclusion holds when longer term impacts are taken into account. This primarily reflects the effectiveness of *V-t-D* in slowing the spread of the disease and, hence, curtailing the duration of the export ban. This comparison is based on the assumption that there are no delays in gaining the approval of reopening export markets. In reality, this may be more difficult with regard to vaccination due to logistical reasons, e.g., additional surveillance requirements for proof of freedom status and delays in removing vaccinated animals following the outbreak (15). The finding that vaccination is favored compared to SO is greater, the

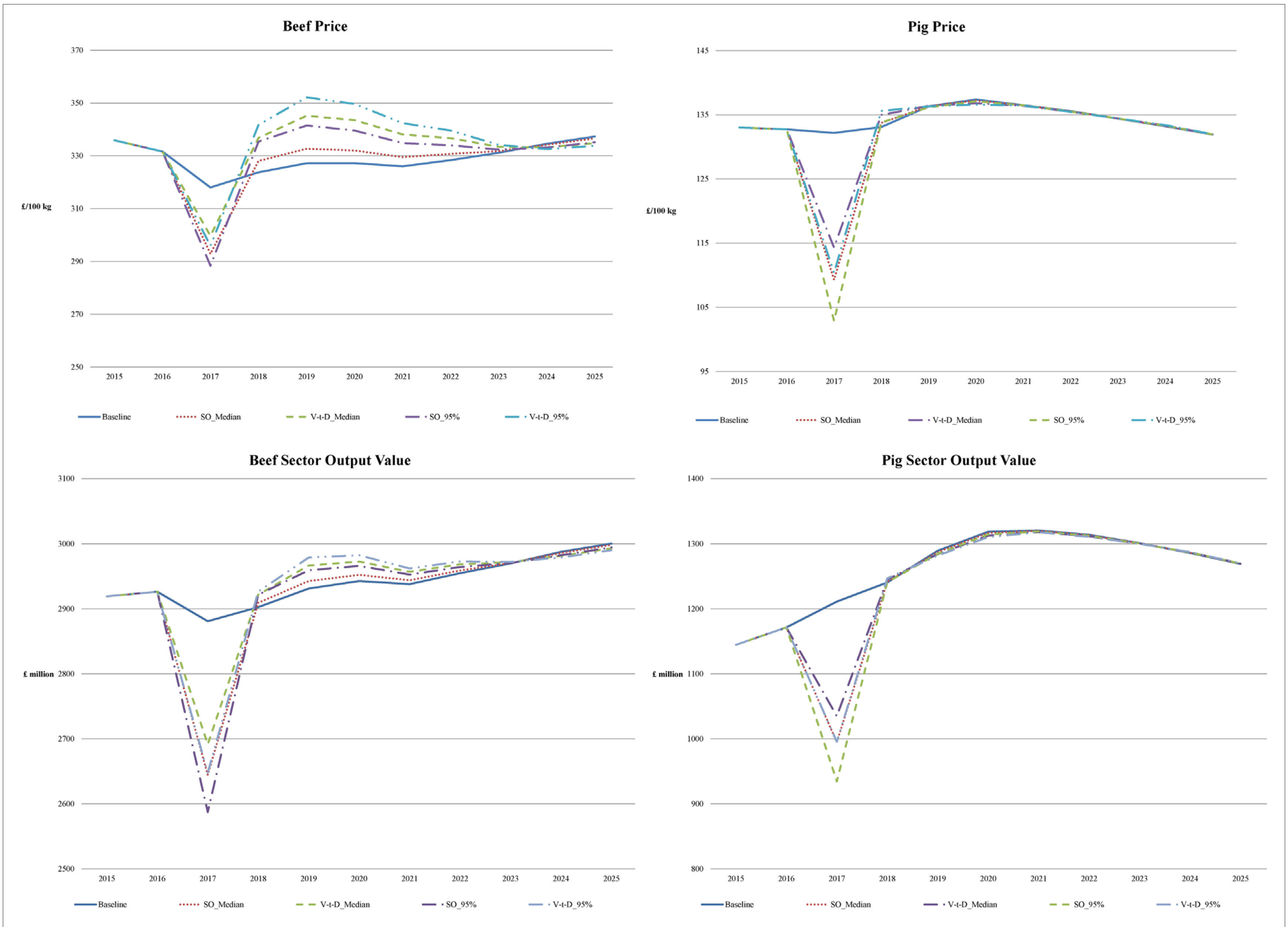

FIGURE 2 | Price and output value paths of the beef (upper left, lower left) and pig (upper right, lower right) sectors 2015-2025 in the main "endogenous displacement" scenario (SO, stamping-out; V-t-D, vaccinate-to-die).

TABLE 4 | Change in total output values of the livestock sectors of 2017–2025.

	Baseline (£ million)	Stamping-out			Vaccinate-to-die		
		5th	Median	95th	5th	Median	95th
Cattle	23,059	−0.8%	−0.9%	−0.9%	−0.4%	−0.4%	−0.5%
Pig	10,045	−2.0%	−2.2%	−2.8%	−1.7%	−1.8%	−2.3%
Sheep	9,832	−2.8%	−3.1%	−4.0%	−2.4%	−2.6%	−3.2%
Total livestock	59,052	−1.1%	−1.2%	−1.5%	−0.8%	−0.9%	−1.1%

more severe the outbreak. However, it should be noted that this analysis focuses on the market impact of the disease outbreak. To make the final choice among the control strategies, other costs such as on farm and administrative costs should also be taken into account.

AUTHOR CONTRIBUTIONS

Substantial contributions to the conception or design of the work: SF, MP, and JD. Acquisition, analysis, or interpretation of data for the work: SF and MP. Drafting the work or revising it critically for important intellectual content: SF, MP, and JD. Final approval of the version to be published: SF, MP, and JD. Agreement to be accountable for all aspects of the work in ensuring the questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved: SF, MP, and JD.

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Expected Net Benefit of Vaccinating Rangeland Sheep against Bluetongue Virus Using a Modified-Live versus Killed Virus Vaccine

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Recurring outbreaks of bluetongue virus in domestic sheep of the US Intermountain West have prompted questions about the economic benefits and costs of vaccinating individual flocks against bluetongue (BT) disease. We estimate the cost of a BT outbreak on a representative rangeland sheep operation in the Big Horn Basin of the state of Wyoming using enterprise budgets and stochastic simulation. The latter accounts for variability in disease severity and lamb price, as well as uncertainty about when an outbreak will occur. We then estimate the cost of purchasing and administering a BT vaccine. Finally, we calculate expected annual net benefit of vaccinating under various outbreak intervals. Expected annual net benefit is calculated for both a killed virus (KV) vaccine and modified-live virus vaccine, using an observed price of $0.32 per dose for modified-live and an estimated price of $1.20 per dose for KV. The modified-live vaccine's expected annual net benefit has a 100% chance of being positive for an outbreak interval of 5, 10, or 20 years, and a 77% chance of being positive for a 50-year interval. The KV vaccine's expected annual net benefit has a 97% chance of being positive for a 5-year outbreak interval, and a 42% chance of being positive for a 10-year interval. A KV vaccine is, therefore, unlikely to be economically attractive to producers in areas exposed less frequently to BT disease. A modified-live vaccine, however, requires rigorous authorization before legal use can occur in Wyoming. To date, no company has requested to manufacture a modified-live vaccine for commercial use in Wyoming. The KV vaccine poses less risk to sheep reproduction and less risk of unintentional spread, both of which facilitate approval for commercial production. Yet, our results show an economically consequential tradeoff between a KV vaccine's relative safety and higher cost. Unless the purchase price is reduced below our assumed $1.20 per dose, producer adoption of a KV vaccine for BT is likely to be low in the study area. This tradeoff between cost and safety should be considered when policymakers regulate commercial use of the two vaccine types.

Keywords: domestic sheep, economics, intermountain west, Monte Carlo simulation, private cost, uncertainty, variability, Wyoming

INTRODUCTION

Bluetongue (BT) is an insect-borne, hemorrhagic, viral disease that affects domestic sheep and other ruminants throughout much of the world, including the US (1). Clinical signs of bluetongue virus (BTV) infection in sheep (*Ovis aries*) can range from mild to severe or fatal; they include widespread edema, internal hemorrhaging, nasal discharge, weight loss, and oral ulcerations. The risk of BT disease can be reduced through vector control (e.g., insecticide application) or vaccination of susceptible flocks. Vector control has been helpful in Europe and Asia (2). However, vaccination has been the most effective method for preventing and controlling BT in Europe (3).

Virus serotypes, vaccine regulations, and day-to-day management practices on rangeland sheep operations in the US Intermountain West are sufficiently different from those in Europe that they may alter the economic effectiveness of vaccination. Costs and benefits of vaccination against BT in the US Intermountain West have not previously been estimated. This is due, in part, to a lack of research on the economic consequences of BT outbreaks in this region. We, therefore, estimate the costs of a BT outbreak in a representative rangeland sheep flock in the state of Wyoming, as well as the costs and expected benefits of vaccinating against BTV. Wyoming is an important sheep-producing state, currently ranking fourth in the US for lamb output, and accounting for 6.7% of the total US sheep inventory (4). The Big Horn Basin of north-central Wyoming (roughly 8,000 km^2; **Figure 1**), in particular, experienced a severe BT outbreak in 2007, which provides a case-study on which to base many of our model parameters and assumptions.

We analyze the economic costs and benefits of two different vaccine types: killed virus (KV) and modified-live virus (MLV). A sheep producer in Wyoming can currently obtain a KV vaccine legally for commercial use, but it involves custom-manufacturing and is, therefore, not readily available and thought to be more expensive. An MLV vaccine, in contrast, cannot be legally obtained for use in Wyoming—due to vaccine safety concerns—yet, is thought to be less expensive and hence more likely to be adopted. These tradeoffs between vaccine safety and vaccine cost (thus adoption) have piqued the interest of animal health policymakers in Wyoming. Unfortunately, the epidemiological data necessary for quantifying the economic value of vaccine safety are not currently available in our study area. But we lay the groundwork for future research and policy debate by determining if either vaccine generates enough benefits to outweigh the private costs of purchasing and administering it. If both vaccines are too costly to justify private investment by sheep producers, then future research and policy debate may be unnecessary. But if an MLV vaccine proves economically attractive for producers, while a KV vaccine does not because of its higher cost, then further research and policy debate may be justified.

BTV and Disease

Bluetongue is a non-contagious, insect-borne viral disease that afflicts sheep, cattle, and other ruminant species (5). BTV is transmitted between susceptible animals by particular biting-midge species of the genus *Culicoides* (*C. sonorensis* in Wyoming). The disease's distribution depends on the range of the relevant midge species, but has historically circumnavigated the globe in temperate and semi-arid climates, between approximately 40° North and 35° South (6). Although BTV has a wide global distribution, symptomatic occurrence of BT disease is most common at the northern and southern boundaries of the virus' range. Virulence is significantly lower in areas where BTV is endemic (i.e., chronically prevalent). This may be due to increased population immunity and co-evolution of the virus and its susceptible hosts (7).

Bluetongue virus, the etiological agent of BT disease, is a member of the *Orbivirus* genus within the *Reovirideae* family. Evolution of BTV is driven by genetic drift, shift, and intragenic recombination (8). Over time, this has led to the establishment of at least 27 known viral serotypes worldwide. In the US, five serotypes were historically identified (BTV 2, 10, 11, 13, and 17), and 10 additional BTV serotypes were recently identified in the southeastern US (7). Viral serotypes vary from each other in characteristics such as virulence and transmission potential (9–11). This may help explain the highly variable morbidity and mortality rates experienced during outbreaks of different viral strains around the globe.

Clinical signs of BT vary in severity depending on the strain of virus and host species affected. Sheep, deer, and antelope (wild or domestic) are relatively more susceptible and affected, whereas cattle and goats are less affected (12–15). In severe cases, the infected ruminant's tongue becomes swollen and discolored and may protrude from the mouth, hence the name "bluetongue." Gross legions on the heart, liver, spleen, kidneys, lungs, and gastrointestinal tract may have extensive hemorrhaging. The course of the disease ranges from 2–15 days, with the majority of symptoms usually appearing within 7 days of infection (16). In mild cases, recovery is swift with costs consisting primarily of weight loss and supportive care. In more severe cases, often in previously unexposed (i.e., naïve) populations, recovery may be prolonged and generate much higher losses. Mortality rates under typical Intermountain West field conditions vary between 4 and 20% of the total exposed population. Death typically occurs 1–8 days after the appearance of symptoms (16).

Economic Costs of BT Outbreaks

Most recent economic studies of BT disease have been conducted in Europe, where several outbreaks of BTV-8 (BTV, serotype 8) have had severe effects on the sheep and cattle industries (17). Most notably, epidemics in the Netherlands during 2006 and 2007 caused large economic losses to sheep and cattle producers. The 2006 outbreak affected 460 farms in the Netherlands, with additional outbreaks occurring in neighboring Belgium, France, Germany, and Luxemburg. The epidemic of 2007 affected more than 6,000 farms in the Netherlands alone. Economic losses totaled 32 million Euros in 2006 and 175 million Euros in 2007 (17). Although the majority of losses occurred within the cattle industry, the sheep industry was also impacted. Within the sheep sector, breeding farms suffered the greatest losses (58% of total sheep morbidity and mortality losses for 2006; 72% of losses for 2007) (17). Velthuis et al. (3) show that vaccination of all adult sheep and cattle is the

FIGURE 1 | Map of the study area, Big Horn Basin, in the state of Wyoming, USA. Images courtesy of the University of Texas Libraries, The University of Texas at Austin (below) and https://en.wikipedia.org/wiki/Outline_of_Wyoming#/media/File:Map_of_USA_WY.svg (top).

best strategy for BT disease control and prevention in Europe, based on benefit–cost ratios.

Although studies estimating the economic consequences of BT outbreaks in Europe offer useful insights, they focus on virus serotypes that do not exist in the US Intermountain West (9). Furthermore, the regulatory and physical environment, scale, and management practices of European sheep operations differ enough from the Intermountain West's extensively managed rangeland sheep flocks to necessitate a separate study.

Recent BT Outbreaks in the US Intermountain West

In 2007, a regional outbreak of BTV-17 (BTV, serotype 17) was first identified in several sheep flocks in the southeastern region of the state of Montana. The disease was subsequently reported in northern regions of the state of Wyoming; first in pronghorn, white-tailed deer, and mule deer in early fall of 2007, and finally in domestic sheep in the Big Horn Basin of northern Wyoming in late fall of 2007 (16). Quarantines were placed on sheep flocks in 17 Montana counties and 3 Wyoming ranches, preventing any off-farm movement.

Bluetongue virus-17 outbreaks had previously occurred in other parts of Wyoming and Montana; however, ranchers and veterinarians reported that Big Horn Basin flocks had not been previously exposed (16). This may be due, in part, to the region's surrounding mountain ranges, which act as a natural barrier to foreign vector populations (16). Outbreaks occur more regularly in other regions of Wyoming that are less geographically protected. In such regions, previously exposed sheep populations seem to experience less severe symptoms than those sheep affected during the Big Horn Basin epidemic. These anecdotal observations provide grounds for further investigation of some veterinarians' hypothesis that sheep populations can build immunity over time if exposed to the virus regularly (16).

The BTV-17 outbreak in Big Horn Basin during 2007 had severe consequences on regional sheep operations. One flock suffered 36% morbidity (500 out of 1,404 sheep) and 20% flock mortality (275 out of 1,404 sheep) (Personal communication with Ranch A operator in 2015). A neighboring ranch was also affected, but fared slightly better: 14% morbidity (233 out of 1,679 sheep) and 0.2% flock mortality (7 out of 1,679 sheep) (16). Recovery from an epidemic of this magnitude can be challenging, given that western US livestock ranches typically have net returns averaging 2–4% per year (18). This thin profit margin can quickly disappear during an unexpected disease epidemic.

BT Prevention Using Vaccines

Vaccination has been used effectively in some regions of the US to control BT in livestock. But because of the region-specific diversity of BT strains, there is limited demand for a vaccine against any one strain. Limited demand has prevented broad-scale commercialization of BT vaccines. Exceptions include a live-attenuated (or modified-live) vaccine against BTV-10, which is approved for use throughout the US, and live-attenuated vaccines against BTV-10, 11, and 17 that are approved for use only in California (19).

Another reason for limited availability and approval of BT vaccines in the US is safety concerns, which differ for the two vaccine types we analyze here. The first vaccine type, live-attenuated or MLV, are relatively cheap to produce and are routinely used in domestic sheep flocks throughout Israel, South Africa, and some US states (limited to certain strains) (20). But use of MLV vaccines is prohibited in some US states because of their potential to revert to virulent type, as well as their ability to infect and be transmitted by insect vectors, thereafter circulating as a field strain. MLV viruses also have the ability to reassort gene segments with field viruses and create novel progeny (7). Finally, if given during pregnancy, MLV vaccines may cause unintended abortions, deformities, and other pregnancy complications (7).

The second type of vaccine is an inactivated autogenous, or KV vaccine. These are typically more expensive to produce than MLV vaccines and require a follow-up dose to attain a protective level of antibodies (19). However, they do not suffer the safety risks associated with MLV vaccines. Specifically, KV vaccines do not revert to virulence, do not reassort genes with field viruses, and do not cause reproductive damage to pregnant females (7).

Speiser et al. (21) tested the ability of two different custom-made BTV-17 vaccines—KV and MLV—to trigger a humoral response in ewes from seven commercial sheep operations in Wyoming. Both vaccines induced protective levels of antibodies, which lasted for at least 1 year and provided passive immunity for lambs. In light of the equal effectiveness of both vaccine types, the next step is to evaluate and compare the vaccines' economic performance.

Our study evaluates the economic costs and expected benefits of vaccinating Wyoming domestic sheep flocks against BTV-17, using either a KV or MLV vaccine. Our results can help inform discussions between sheep producers, vaccine manufacturers, the State Veterinarian, and Livestock Board about potential approval and commercial sale of a BTV-17 vaccine for Wyoming. Currently, Wyoming producers can custom-order a KV vaccine manufactured from a recent isolate taken from an outbreak occurring in their region. An MLV vaccine for BTV-17 is not currently available for producer use outside of California, but the potential exists to legalize its importation into western sheep-producing states such as Wyoming (Personal communication with Dr. Jim Logan, Wyoming State Veterinarian in 2016). Before engaging in a debate about MLV vaccine legalization, animal health policymakers need to know if either vaccine would generate positive economic net benefits for producers.

MATERIALS AND METHODS

Expected Profit Maximization

The theoretical framework for this study is expected profit maximization. We assume a sheep producer's expected profit depends on their decision to vaccinate (or not vaccinate) their flock against BT. When combined with two possible states of nature (BT affects their flock, or it does not), there are four possible outcomes: (1) vaccinate and sheep contract BT anyway; (2) vaccinate and sheep do not contract BT; (3) do not vaccinate and sheep contract BT; (4) do not vaccinate and sheep do not contract BT. The producer organizes these four possible outcomes into two different expected profit functions: one for the decision to vaccinate, and one for the decision not to vaccinate. They then compare the two expected profits to decide whether or not to vaccinate.

The first step in identifying the expected profit maximizing decision is to determine the probability of occurrence for each of the four possible outcomes. Our chosen probabilities are based on historical data of the disease (16) and first-hand producer knowledge for the Intermountain West (Personal communication with Ranch A operator in 2016). To represent differences in disease prevalence throughout Wyoming, we calculated the expected net benefit associated with outbreaks occurring every 5, 10, 20, or 50 years.

Rangeland Sheep Production Budgets

The next step of our analysis is updating an existing sheep enterprise budget, for a representative operation with 640 breeding ewes (1,404 sheep in total) (22), to US$2014 prices using indices of prices paid by Wyoming farmers and ranchers from 2010 to 2014 (23). Prices assumed in our analysis are reported in Table S1 in Supplementary Material. The updated budget provides an outline of management activities, costs, and revenues for a 1-year production calendar. It provides baseline estimates of profit, which we later adjust to reflect the costs of vaccinating sheep against BT, and the cost of a BT outbreak itself. A summary of the baseline budget is available in Table S2 in Supplementary Material. Munsick (24) provides a more detailed version of the baseline budget.

BT Outbreak Costs

To estimate the cost of a BT outbreak, we reconstruct the series of events experienced by an anonymous producer during the 2007 BT outbreak in the Big Horn Basin of Wyoming. The dates they report imply a particular subset of production activities being disrupted. If the outbreak's timing had differed substantially from this, an alternative subset of activities would be disrupted, resulting in different outbreak costs. The anonymous producer's outbreak unfolded as follows. BT symptoms were detected September 1st and ended October 15th, encompassing 45 days of symptomatic disease within the flock. An on-site flock quarantine was imposed throughout the duration of the outbreak. The end of vector season occurred on the first hard freeze (29°F or below) on October 15th (23). An additional asymptomatic quarantine period of 14 days commenced on October 16th and extended to October 30th. This lengthened the total BT outbreak quarantine period to 59 days (Personal communication with Ranch A operator in 2015).

Tangible costs that a producer incurs during an outbreak include death loss, supportive care, pharmaceuticals, loss of condition, labor, and veterinarian fees. Intangible costs, such as stress and other emotional impacts, are not quantified here but are no less impactful. To calculate lamb death loss, we multiply the number of lambs lost to BT by a 25-year mean market value, $130/cwt, which we derive from a distribution of real historical lamb prices (1990–2014) from the Centennial Livestock Auction near Fort Collins, CO, USA (25). We assume that our representative operation markets 90-pound feeder lambs.

Ewe death loss is calculated by multiplying the number of ewes lost to BT by the economic value of an average-aged ewe in the flock. Based on conversations with regional producers (Personal communication with Peter John Camino, former President Wyoming Woolgrowers Association and with Ranch A operator in 2015), our representative flock's replacement ewes are developed from within the operation. Therefore, the loss of an adult ewe due to BT is considered a capital loss. Specifically, it is equal to the cost of developing an identical replacement minus the cull value. This capital loss is then added to the discounted cull value lost to determine overall economic value lost when a ewe dies from BT. Details of the cost to develop a replacement ewe can be found in Munsick [(24), p. 16]. We use a similar method to calculate costs associated with ram death loss from BT [(24), p. 17]. Throughout our analysis, we use a 7% rate to discount the operation's future costs and benefits to the present. This rate is commonly used for agricultural investments; it accounts for a 4% real rate of return on investment plus a 3% risk premium (18).

Another factor in the cost of a BT outbreak is providing supportive care to infected sheep. Substantial swelling in the face and throat of infected sheep requires a producer to provide a source of nourishment other than forage or hay. Ranch A accomplished this by mixing creep feed with water and administering the mixture directly to infected animals *via* feeding tube. Infected sheep that eventually recover begin to show signs of improvement after 7 days of creep-feeding. Those that eventually die do so after 10 days of creep-feeding (Personal communication with Ranch A operator in 2015). Infected lambs consume 2 lbs of creep feed (before adding water) per day while ewes and rams consume 3 lbs per day.

Pharmaceuticals needed during an outbreak are also included in supportive care costs. Direct vector control, for example, is beneficial when used to supplement vaccination in preventing further BT infections once an outbreak is detected [(2); Personal communication with Dr. Jim Logan, Wyoming State Veterinarian in 2016]. Permethrin is an affordable, widely available insecticide approved for direct use on livestock, including sheep. It is helpful in the control of the BT vector, *Culicoides* spp. (2). However, application is labor intensive [(2); Personal communication with Ranch A operator in 2015], and its effectiveness as a sole control measure (which we do not quantify in this analysis) is incomplete (26). We assume the treatment is repeated every 2 weeks throughout the course of the outbreak, totaling three treatments from September 1st to October 15th.

A significant portion of BT mortality is caused by secondary respiratory infections (16). Nuflor is an example of a synthetic, broad-spectrum antibiotic that aids in prevention and treatment of bacterial pathogens (e.g., pneumonia) that commonly occur during a BT outbreak (Personal communication with Dr. Matt Cherni, practicing large animal veterinarian in 2015). Nuflor label instructions call for a two-dose treatment, the second being administered 48 h after the first. Dexamethasone is used as an anti-inflammatory and may be administered simultaneously with Nuflor to the entire flock. The drug is relatively affordable and is effective in treating inflammatory symptoms common for BT, such as fever, pain, and swelling.

Due to a lack of data, we assume no loss in ewes' reproductive efficiency or condition during a BT outbreak. However, we do account for a loss of condition in market lambs during the year of the outbreak. We assume a 10% live-weight loss (i.e., 90 lb lamb × (1 − 0.10) = 81 lb live weight, or a 9 lb loss per lamb) in surviving infected lambs which are marketed soon after recovery (Personal communication with Ranch A operator in 2015).

Labor costs include additional hired labor required to manage a BT outbreak. Many operations will fulfill additional labor requirements with longer hours for themselves and their families, but we assume additional owner labor is unavailable and, therefore, hired labor must be increased. The amount of additional labor necessary to cope with an outbreak is estimated based on Ranch A operator's experience in 2007.

A BT outbreak generally does not involve extensive veterinarian resources. However, some visits from State and Federal officials may be necessary. The use of these public resources represents a social cost (as opposed to private cost) of the disease, and should not be overlooked. Similarly, research funded with public dollars to better understand BT represents an additional social cost (and social benefit). Our study focuses on private costs to sheep producers and, therefore, does not attempt to estimate the public cost of State or Federal veterinarians' visits, BT research, or other public resources used during an outbreak.

BT Vaccination Costs

The cost of purchasing and administering a BT vaccine is based on pharmaceutical companies' recommendation that producers annually vaccinate their entire flock. To improve efficiency and decrease vaccination labor costs, we assume that a producer vaccinates their entire flock at the same time as deworming, on June 1st. This also allows for passive immunity to begin to wane in the newborn lamb crop (Expert opinion of co-author, Miller). Since the entire flock is already being handled and run through the chute for deworming, we assume it takes only 10 additional seconds to vaccinate for BT. The follow-up dose, required only if using the KV vaccine, can be given at any point after a minimum of 3 weeks has passed since the first dose. However, for the vaccine to produce desired levels of antibodies, the second dose must be given at least 7 days prior to flock exposure to the disease. For many producers, this amounts to vaccinating their flock twice before moving to summer range, or possibly administering the follow-up dose at some point during summer. If producers decide to vaccinate their flock separately from any existing handling sessions, the cost of labor will increase beyond what is reported in our analysis. Total vaccination costs are calculated by summing the cost of purchasing the vaccine and the cost of labor needed to administer it during existing handling sessions.

MLV Vaccination Cost

An MLV vaccine contains whole viruses that are able to grow and multiply within a host body. They stimulate the host immune system to create antibodies, yet do not typically cause actual disease in the host. Because the vaccine contains live active viruses, only one annual injection is needed (27).

A major side-effect of the MLV BT vaccine is the potential to cause abortions in pregnant ewes or malformations in their lambs. We do not include risk of abortions in our cost estimate, because we assume that producers administer the vaccine properly, i.e., not during pregnancy. There is also a risk that the modified virus will revert to virulent type, causing the vaccinated animal to become sick, or to infect and be transmitted further by the vector midges (28). This "escape" risk represents an external or social cost and is not borne by producers directly. Therefore, it is outside the scope of this analysis, which focuses solely on producer's private costs. These two risks limit the use of an MLV vaccine to between March 31 and June 1 (i.e., after lambing and before the height of vector season).

The only available MLV vaccine for BTV-17 is approved for use strictly in California. For use in Wyoming, the producing company would need to seek USDA approval for distribution and use in other states, and then solicit a formal request from the State Veterinarian. To do this they must provide adequate documentation of efficacy, product safety, and USDA licensure (Personal communication with Dr. Jim Logan, Wyoming State Veterinarian in 2015). We assume a retail purchase price for such an MLV vaccine of $0.32 per dose, based on the price advertised for a similar vaccine on the California Wool Growers Association's website (http://cawoolgrowers.org/vaccines/bluetongue.html).

KV Vaccination Cost

An autogenous or KV vaccine is produced using virus strains isolated from infected tissue samples using a cell culture system (29). As a USDA-licensed, restricted-use product, KV vaccines against BT are available for use only under veterinarian supervision. However, they involve no seasonal restrictions on its use, no risk of vector transmission, and no risk of abortion if used in pregnant ewes. The vaccine can be made as a monovalent (single antigen), bivalent (double antigen), or trivalent (triple antigen) vaccine. However, our analysis focuses on a monovalent vaccine for BTV-17.

Production of a KV vaccine takes approximately 12 weeks. Therefore, production and field-deployment of this type of vaccine might be infeasible if begun after the onset of an outbreak. However, virus isolates taken from a specific site may be used for up to 15 months from the date of isolation from tissue (30). An additional 24 months of use may be granted if vaccine efficacy has been shown and a viable threat of disease still exists. The use of a KV vaccine is also restricted to the BTV isolate's source flock. However, permission for use in other flocks may be granted by the State Veterinarian (30). Retail pricing for a KV vaccine is assumed to be approximately $1.20/dose, which includes a 20% markup by a private veterinarian (Personal communication with Newport Laboratories, Worthington, MN, USA, in 2012).

BT Vaccination Benefits and Net Benefits

Recent studies have found the efficacy of both MLV and KV vaccines under controlled conditions to range from 84 to 100% (21). We assume a conservative 84% effectiveness for both vaccines. Vaccine effectiveness is modeled by reducing the number of infected sheep by 84%, which propagates through the enterprise budget by reducing the number of sheep experiencing morbidity or mortality and the total hours of supportive care required.

The next step in our analysis is to calculate expected annual net benefit of vaccinating. We calculate this for both the MLV and KV vaccine, and for outbreak intervals of 5, 10, 20, and 50 years. To calculate expected annual net benefit, we first determine the expected benefit of vaccinating in a given year, accounting for time value of money and uncertainty in outbreak timing. Even if a producer knows the outbreak interval for their area (e.g., 10 years), they cannot predict the exact year in which an outbreak will occur. Therefore, we calculate the present value (PV) of benefit for each possible year in which the outbreak could occur (e.g., 1–50). We then annualize each of these PVs. Next, we multiply each annualized benefit by the probability of an outbreak occurring in a given year (e.g., 0.02). This generates a weighted annualized benefit for each year. Finally, we sum the weighted annualized benefits for each year to obtain an average or expected annual benefit over the given outbreak interval. This approach accounts for time value of money as well as uncertainty about an outbreak's timing within a given interval. From this expected annual benefit, we then subtract the annual cost of vaccination to obtain expected annual net benefit of vaccination. This four-step calculation is summarized in Eq. 1:

$$\text{Expected Annual Net Benefit} = \sum_{t=0}^{N-1}\left[\frac{\text{Benefit}}{(1+i)^{t}} * \frac{i}{1-(1+i)^{-N}} * \frac{1}{N}\right] - \text{Annual Cost}, \quad (1)$$

where N is the outbreak interval (e.g., $N = 5$, 10, 20, or 50); t is the year in which an outbreak occurs (e.g., $t = 0$ indicates it occurs in the current year); *Benefit* is the undiscounted benefit of having a vaccinated flock when an outbreak does occur; i is the discount rate; and *Annual Cost* is the real cost incurred per year to vaccinate a flock against BT disease. In summary, the first term inside the brackets discounts the benefit of vaccinating based on the year in which the outbreak occurs. This adjusts for a producer's time value of money (i.e., $1 of benefit received today tends to be valued more highly than $1 of benefit received in a future year). Next, the middle term inside the brackets annualizes the PV of benefit, spreading it evenly across the entire outbreak interval after accounting for the discount rate. The third and final term inside the brackets weights the annualized benefit by its probability of occurring (i.e., by the probability of an outbreak occurring in year, t). This three-step process is repeated for every t (i.e., for every possible year in which the outbreak could occur, given a particular outbreak interval). The resulting set of weighted annualized benefits is then summed to give the expected annual benefit. Finally, annual cost of vaccinating a flock is subtracted from expected annual benefit, resulting in expected annual net benefit of vaccination.

Incorporating Variability: @Risk Simulation

For the final step of our analysis, we use the software program @Risk to conduct a Monte Carlo simulation, which allows three parameters in our model to vary (26): lamb price, morbidity rate, and mortality rate. Monte Carlo simulation is a technique that randomly draws a set of parameter values (where each set represents an "iteration") from a probability distribution (29), and then uses those values in all calculations involving the three parameters. Each simulation involves running 50,000 iterations.

By simulating variability in lamb price, morbidity rate, and mortality rate, we are able to account for the inherent variability of outbreaks occurring in different years and at different geographic locations. Producers are generally well-aware of changing market and disease conditions and, therefore, desire information about vaccine performance during worst-case and best-case scenarios, not just on average. The distributional information generated through Monte Carlo simulation helps producers identify strategies that are robust to a range of possible outcomes.

We first simulate a distribution for outbreak cost (**Figure 2**), which then serves as an intermediate input to the simulation of distributions for expected annual net benefit, one each for the KV and MLV vaccines. Each of these three distributions is influenced by the input distributions chosen for lamb price, morbidity rate, and mortality rate. We fit a log-logistic distribution to observed lamb prices (28) from the Fort Collins auction barn during November 1990 to November 2014 (adjusted to US\$2014; see Figures S1 and S2 in Supplementary Material). Its parameters are set to the following values: $\gamma = 0.58805$, $\beta = 128.31$, $\alpha = 7.0474$, minimum = 46.53, maximum = 229. Truncation at the minimum and maximum values allows the lamb price to fall one SD (\$0.31/pound) below or above the historical price range.

We model the morbidity rate as a uniform distribution with a minimum = 0.06 and maximum = 0.36. Similarly, we model the mortality rate as a uniform distribution with a minimum = 0.046 and maximum = 0.20. Parameter values for the mortality and morbidity rates are based on observations from a previously naïve flock in the Big Horn Basin (for maximum values), and from a routinely exposed flock in Johnson County, Wyoming (for minimum values). More details of the rationale behind the distributions chosen are presented in Munsick [(24), p. 32–36]. Table S3 in Supplementary Material provides @Risk formulas for the three input distributions.

RESULTS AND DISCUSSION

BT Outbreak Costs

Table 1 provides outbreak costs assuming mean values for morbidity rate (21%), mortality rate (12.3%), and lamb price (\$1.30 per pound). **Figure 2** depicts the distribution of simulated outbreak costs for the operation, accounting for variability in lamb price, morbidity, and mortality. Costs associated with a BT outbreak can be disaggregated into several categories.

Total death loss is the combined loss of ewes, rams, and lambs due strictly to a BT outbreak. Although ram death loss is static, ewe death loss is a function of the variable lamb price and is,

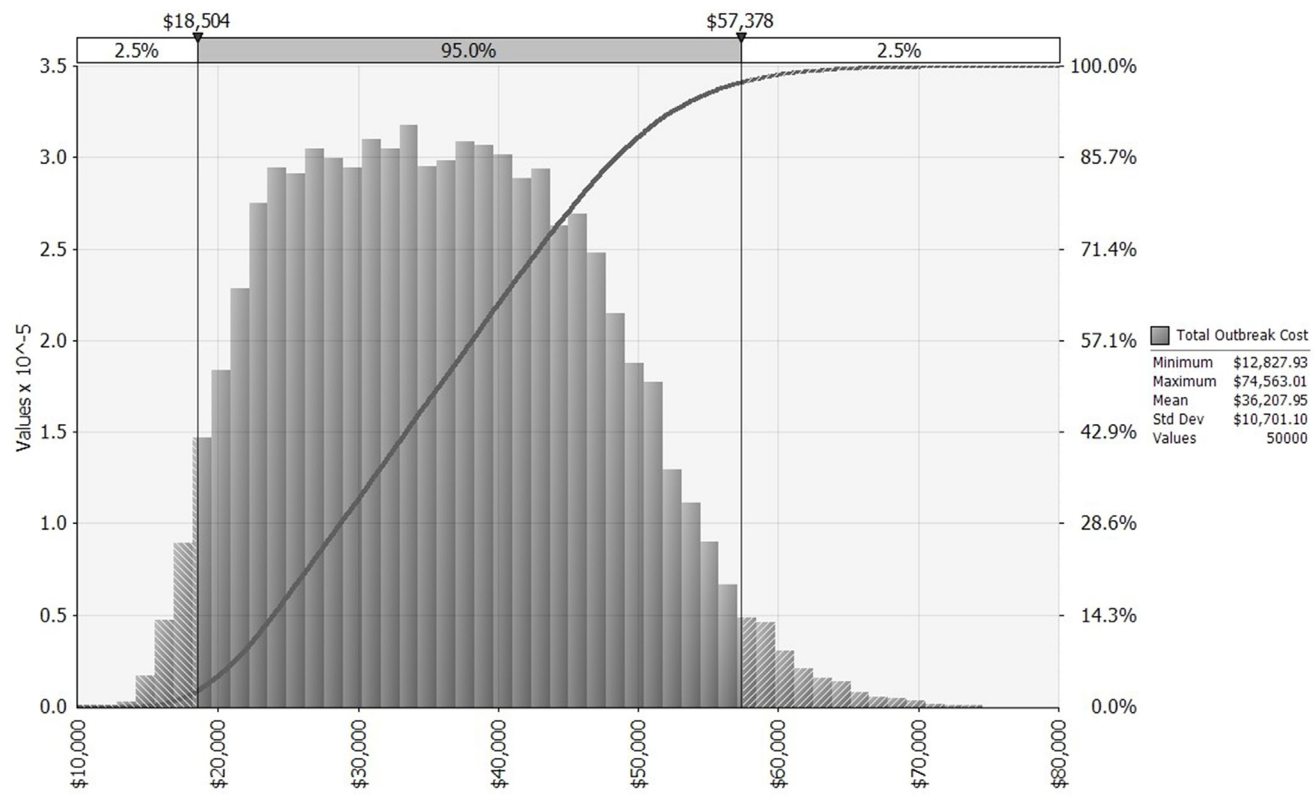

FIGURE 2 | Distribution of bluetongue outbreak costs for a 640-ewe operation, allowing morbidity, mortality, and lamb price to vary across 50,000 iterations, based on historical distributions of these three random variables. *x*-Axis shows outbreak costs measured in US\$2014. The left vertical axis and gray bars present a histogram for outbreak cost. The right vertical axis and dark gray curve present a cumulative probability distribution for outbreak cost [i.e., pr(Outbreak Cost) ≤ \$X = Y%].

therefore, a distribution. After all, the death of a ewe triggers retention of an extra replacement lamb, which would have otherwise been sold at the variable lamb price. Lamb death loss is also a function of the variable lamb price, as well as morbidity and mortality rates.

Supportive care costs include tubing infected animals with a creep feed/water mixture and administering necessary pharmaceuticals as needed. Creep feed costs are driven by the variable morbidity and mortality rates. Pharmaceutical costs include direct application of permethrin insecticide spray, administration of Nuflor for all clinically infected cases, and administration of dexamethasone as needed. Additional costs include weight loss on surviving infected lambs, labor, and veterinarian costs (only those paid by the producer).

BT Vaccination Costs

The cost of vaccination includes both the cost of purchasing vaccine and the labor to administer it. Cost of hired labor is assumed to be $10.64/h (31) adjusted by a producer price index of 1.091. Purchase price of the vaccine is estimated at $0.32/dose for the MLV vaccine and $1.20/dose for the KV vaccine. **Table 2** shows the vaccine and labor costs for vaccinating the entire flock, using the MLV versus KV vaccine. Costs reported for the KV vaccine include both the first dose and the required follow-up dose.

BT Vaccination Benefits

The benefit of vaccinating sheep against BT is a reduction in the proportion of the flock affected when the virus strikes. In a 640-ewe flock that has been vaccinated, the average number of morbidities and mortalities is reduced from 285 and 167 (without vaccination), respectively, to just 46 and 27 (with vaccination). This reduces the cost of an outbreak from an average of $36,207 (without vaccination) to $5,243 (with vaccination). Thus, on average, the benefit of vaccinating is $30,964 per outbreak. This benefit ranges, however, from as little as $11,325 to as much as $63,183, depending on the outbreak's severity and the lamb price. Because the benefit of vaccinating depends so heavily on outbreak cost, their distributions are shaped similarly (compare **Figure 2** to Figure S3 in Supplementary Material).

Of the three random variables in our analysis, BT mortality rate has the greatest influence on outbreak cost and hence vaccination benefit. Lamb price has the second greatest influence, followed by BT morbidity rate. **Figure 3** shows a tornado graph (using the "regression coefficients" option in @Risk) of relative influence of the three random variables on vaccination benefit. Regression coefficients indicate the amount of change that will occur in a dependent variable due to a change in an independent variable. For example, increasing the lamb price by 1 unit will result in a 0.35 unit increase in the benefit of vaccination.

The total benefit of administering a BT vaccine, over a producer's career, depends on how often their flock is exposed to the virus. Ideally, a producer would only have to vaccinate in years when the virus is known to be a threat. Unfortunately, society's ability to predict an outbreak is currently limited, so producers must decide ahead of the risk season each year whether to vaccinate. Before making the vaccination decision, producers should compare the annual cost of vaccinating against its expected annual benefit, to determine expected annual net benefit.

TABLE 1 | Bluetongue outbreak costs for a 640-ewe operation (US$2014).

Supportive care costs		**Death loss**	
Creep feed costs		Lamb death loss	9,677
Lambs (lived + died)	1,235	Ewe death loss	15,161
Ewes (lived + died)	1,783	Ram death loss	1,275
Rams (lived + died)	54	*Total death loss*	$26,113
Pharmaceutical costs		**Other costs and losses**	
Permethrin (insecticide spray)	38	Lamb weight loss	684
Nuflor (pneumonia prevention)	2,832	Veterinarian cost	0
Dexamethasone (inflammation)	28	Labor cost	3,439
Total supportive care costs	$5,970	*Total other*	$4,123
		Total outbreak cost	$36,206
		% of Baseline profit	35%

Reported costs are calculated using the mean morbidity rate (21%), mean mortality rate (12.3%), and mean lamb price ($1.30/pound).

TABLE 2 | Cost of annual bluetongue vaccination for a 640-breeding-ewe operation (entire flock at time of vaccination is 1,423 sheep) using a modified-live virus (MLV) versus killed virus (KV) vaccine (US$2014).

	MLV	KV
# Doses required per sheep	1	2
Total vaccine cost	455	3,416
Total labor cost	42	84
Total cost per year	$497	$3,500
Average cost per sheep	$0.35	$2.46

BT Vaccination Net Benefits

To calculate expected annual net benefit of vaccination, we must assume how frequently the virus will strike. **Table 3** reports the mean value of expected annual net benefit for outbreak intervals of 5, 10, 20, and 50 years. Expected annual net benefit of vaccination tends to be higher for MLV than for the KV vaccine (**Table 3**; **Figure 4**). This is because the MLV vaccine is cheaper to purchase and requires only one dose per year, whereas the KV vaccine has a higher assumed purchase price and requires a follow-up dose. The higher expected annual net benefit for MLV than for KV holds true across all outbreak intervals (**Table 3**). More specifically, MLV yields positive expected annual net benefit (based on its median) up to 69 years between outbreaks (**Figure 5**). KV vaccine, in contrast, yields positive expected annual net benefit up to just 9 years between outbreaks (**Figure 5**).

Figure 5 also reveals that, as outbreak interval lengthens, expected annual benefit decreases. This is because benefit is assumed to occur just once during a given interval. Thus, as outbreak interval lengthens, the annualized benefit of vaccination gets smaller and smaller, whereas the annual vaccination cost remains the same. This causes the expected annual net benefit to decrease as outbreak interval lengthens (**Table 3**).

Turning to variability, the distributions of expected annual net benefit for MLV versus KV are shown in **Figure 4**, for a 10-year outbreak interval. The shape of these distributions is similar to those for 5, 20, and 50-year outbreak intervals (not shown). Note that the two distributions in **Figure 4** are identically shaped and differ only in their mean values. This is because they both derive

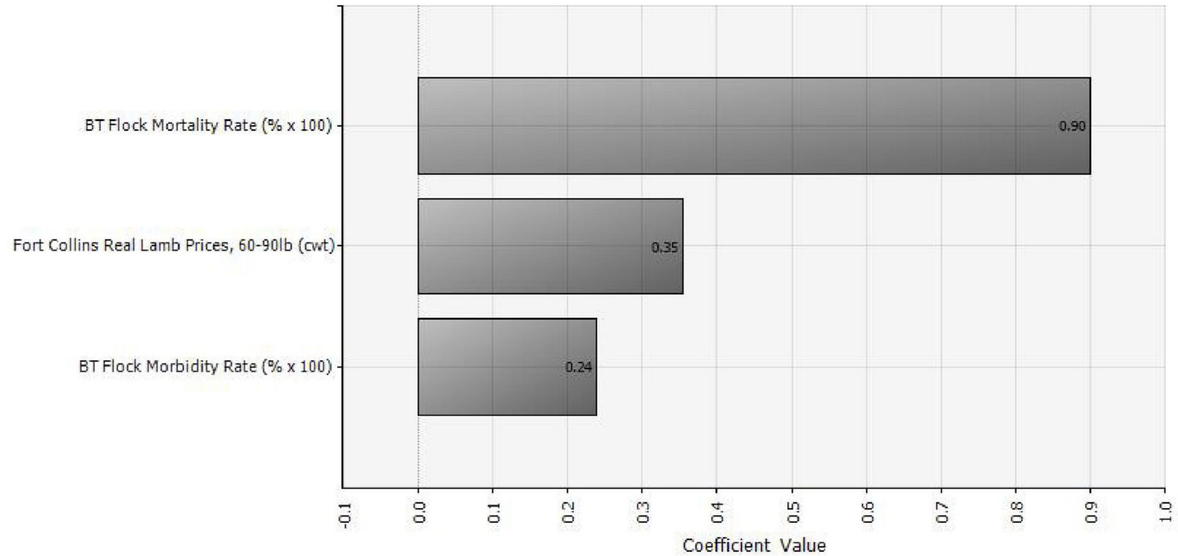

FIGURE 3 | Relative influence of three different random variables (lamb prices, morbidity, and mortality) on the benefit of vaccinating against Bluetongue disease (with either modified-live virus or killed virus), assuming an annual vaccination strategy.

TABLE 3 | Mean value of expected annual net benefit (US$2014) for two different vaccine types [modified-live virus (MLV), killed virus (KV)], administered annually, under different outbreak intervals (5, 10, 20, and 50 years).

	Outbreak interval			
	5 years	**10 years**	**20 years**	**50 years**
MLV	$6,129	$2,816	$1,159	$165
KV	$3,126	–$187	–$1,843	–$2,837

from the same outbreak cost distribution (**Figure 2**), which is based on a log-logistic lamb price distribution (Figure S1 in Supplementary Material) and uniform morbidity and mortality distributions (Table S3 in Supplementary Material). The identical distribution of expected annual net benefit for MLV versus KV (**Figure 4**) also reflects our assumption that both vaccines are equally effective. Given their many similarities, the two distributions differ only because the MLV vaccine is assumed to be $3,003 cheaper than KV (precisely the difference between the two distributions' means). The purpose of **Figure 4** is to illustrate the dramatic implication this cost difference has on the probability of MLV versus KV generating positive expected annual net benefit. For a 10-year outbreak interval, MLV has a 100% chance of generating positive expected annual net benefit, whereas KV has only a 42% chance. This cost-driven reduction in the probability of breaking even, on average, will reduce producers' willingness to adopt KV as compared to MLV.

Table 4 reports, for various outbreak intervals, the percent of simulation iterations in which vaccination enjoys positive expected annual net benefit. The KV vaccine's probability of yielding positive expected net benefit falls sharply from 97 to 42% as outbreak interval lengthens from 5 to 10 years. And for producers facing a 20-year or longer outbreak interval, there is zero probability that a KV vaccine will generate positive expected net benefit. For the MLV vaccine, in contrast, there is a 100% chance of positive expected net benefit for outbreak intervals of 5, 10, and 20 years. Only at an outbreak interval of 50 years does this probability fall to 77%. This reflects, again, the MLV vaccine's lower assumed cost, and highlights its important economic implications.

Epizootic versus Endemic Outbreaks

A sheep operation's location and history of disease play an important role in the expected net benefit of vaccinating. Producers in high-frequency, low-virulence areas, who face regular but mild outbreaks, may face a different risk than producers in low-frequency areas with no recent history of the disease and thus naïve sheep flocks and severe outbreaks.

Table 5 reports two iterations from the @Risk simulation to put expected annual net benefit of vaccination (using an MLV vaccine) into a geographic context. We have hand-selected two iterations that share the same historical mean lamb price, $130.36 (25), but exhibit different outbreak characteristics. One iteration represents conditions typical of the Big Horn Basin, where sheep flocks have experienced outbreaks relatively infrequently (e.g., roughly every 10 years) and relatively severely (e.g., 22% morbidity, 20% mortality). The other iteration represents conditions typical of eastern Wyoming, where flocks have experienced outbreaks more frequently (e.g., roughly every 5 years) yet less severely (e.g., 6% morbidity, 7% mortality). The Big Horn Basin iteration is chosen from among the 50,000 MLV iterations underlying **Figure 4** (i.e., a 10-year outbreak interval). The eastern Wyoming iteration is chosen from among 50,000 MLV iterations underlying a similar (unpublished) figure for a 5-year outbreak interval.

Vaccination is less beneficial for producers located in a "lower" risk (i.e., more frequent thus less severe outbreaks) area compared

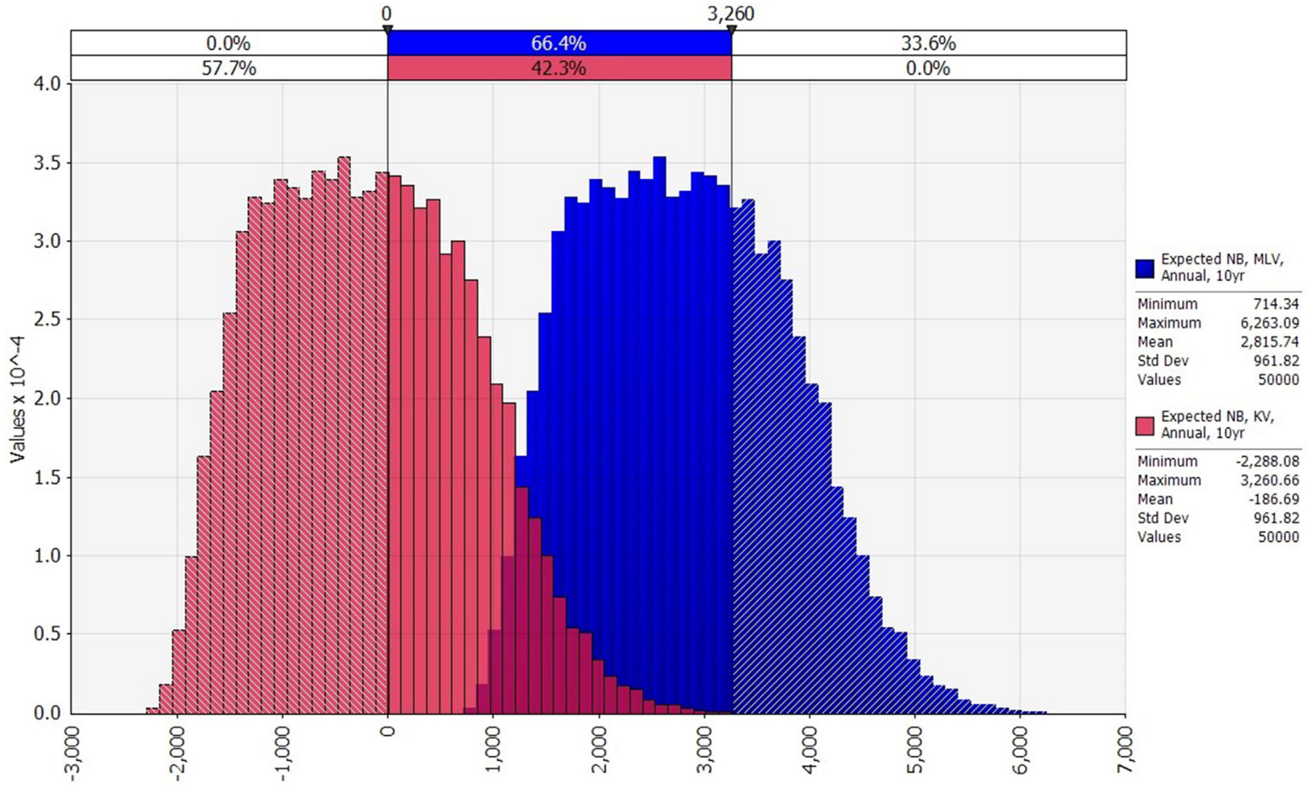

FIGURE 4 | Comparison of the distributions of expected annual net benefit for modified-live virus (MLV) and killed virus (KV) (US$2014), assuming an annual vaccination strategy, and 10 years between outbreaks. Variability in any one of the vaccine's expected annual net benefit is due to variability in lamb price, Bluetongue (BT) morbidity rate, and BT mortality rate. MLV's net benefit exceeds the maximum net benefit of KV in 33.6% of the 50,000 iterations.

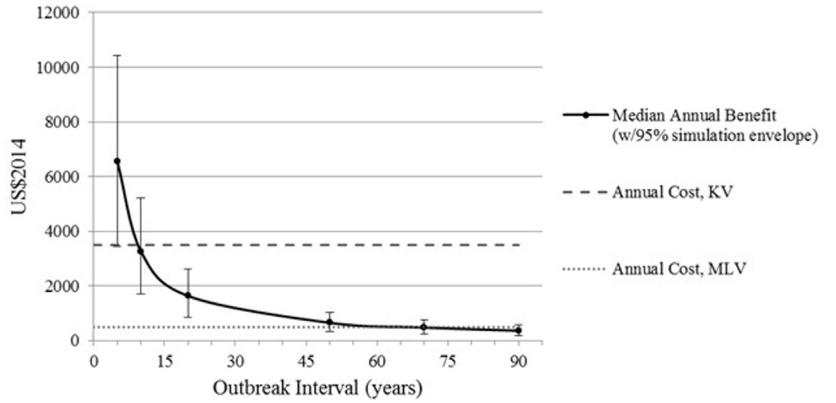

FIGURE 5 | Median expected annual benefit for both modified-live virus (MLV) and killed virus (KV) vaccines, with bars reflecting the 95% simulation envelope (i.e., 2.5th and 97.5th percentile). Annual cost of MLV and KV vaccines. Intersection of a vaccine's cost curve with the median benefit curve indicates the outbreak interval at which that vaccine's median annual benefit no longer exceeds its annual cost. All benefits and costs are reported in US$2014.

to those in a "higher" risk (i.e., less frequent thus more severe outbreaks) area (**Table 5**). Ironically, producers that experience outbreaks less frequently may also be less likely to administer the vaccine (32). For producers in areas with shorter outbreak intervals and lower risk of high-severity outbreaks (e.g., eastern Wyoming), lamb prices may be a significant factor in their decision to vaccinate or not. Vaccination might not be profitable in years with unusually low lamb prices. Increased BT forecasting would give producers in low-risk areas the ability to vaccinate only in years when lamb prices are high enough to make vaccination profitable, thereby decreasing vaccination costs. This is a promising area for future research.

TABLE 4 | Percentage of iterations in which vaccination with modified-live virus (MLV) versus killed virus (KV) has positive expected annual net benefit, for various outbreak intervals, on a 640-ewe operation.

	Vaccination strategy	
Outbreak interval (years)	**MLV (%)**	**KV (%)**
5	100	97
10	100	42
20	100	0
50	77	0

TABLE 5 | Two hypothetical outbreaks in Wyoming, depicting two different iterations from a single simulation—one akin to eastern WY (more frequent but less severe outbreaks) and one akin to the Big Horn Basin (less frequent but more severe outbreaks)—using annual vaccination with a MLV vaccine on a 640-ewe operation.

	Eastern WY	Big Horn Basin
Outbreak interval (years)	5	10
Morbidity rate	0.06	0.22
Mortality rate	0.07	0.20
Lamb price (per hundredweight)	$130.36	$130.36
Annual net benefit	$3,253	$4,329

Implications for Vaccine Approval in Wyoming

We have modeled and compared the costs and benefits for both MLV and KV vaccines. Recall, however, that the MLV vaccine requires a rigorous authorization process before legal distribution and use can occur in Wyoming. To date, no company has requested to make an MLV vaccine commercially available for use in Wyoming. It may be more feasible for Wyoming producers to obtain approval for a custom-made KV vaccine because it poses less risk to sheep reproduction and less risk of escape. However, based on our estimated purchase price of $1.20 per dose, a KV vaccine would be seven times more expensive to manufacture and administer than an MLV vaccine (**Table 2**). This is sufficiently expensive that a producer who faces an outbreak interval longer than 5 years is unlikely to adopt it because of its low probability of generating positive expected annual net benefit. An MLV vaccine, in contrast, has a high probability of generating positive expected annual net benefit for producers who face even a 50-year outbreak interval.

This suggests further research is needed to quantify the value of vaccine safety and determine whether it is high enough to justify the current ban on MLV vaccines. The MLV vaccine's risk of escape would need to be sufficiently costly to make the MLV vaccine's cost equal to or greater than the KV vaccine's cost. If, however, MLV were shown to be less expensive than KV, even after accounting for the external costs of potential escape, then rules banning MLV vaccines may be economically inefficient.

The risk of escape is real, not simply hypothetical. A recent outbreak of BTV-3 in India, for example, was traced back to Western virus strains, and is believed to have been initiated by reassortment of the virus through MLV vaccination (33). External costs of MLV vaccination may be difficult to quantify, but further research is needed so animal health officials can make economically informed decisions regarding the most efficient type of vaccination against BT disease.

Limitations

The outbreak costs estimated in this paper are large enough to pose an economic threat to producers, yet do not fully reflect the damage that a severe outbreak can inflict on an individual operation. Intangible costs such as negative impacts on personal health, family dynamics, and community relationships are also important. An outbreak of this magnitude may have severe and long-lasting effects on an individual or family and their operation (Personal communication with Ranch A operator in 2015). We do not attempt to place an economic value on these intangible impacts and have, therefore, underestimated the cost of a BT outbreak and, subsequently, the expected annual net benefit of vaccinating against it.

In addition to expected annual net benefit—the focus of our analysis—risk preference and other behavioral tendencies are likely to influence an individual producers' vaccination choice. Risk preferences range from risk-loving to risk-averse, with risk-neutral falling between the two. We have analyzed BT vaccination from the perspective of a risk-neutral producer, i.e., one who cares only about maximizing the expected value of a decision, without concern for potential variability in the outcome of that decision. In contrast, we would expect a risk-averse producer to be more likely to vaccinate their flock against BT. Given the robustness of our results for the MLV vaccine—indicating a positive expected annual net benefit under a wide range of possible conditions—inclusion of risk aversion would reinforce our findings that an MLV vaccine against BT is likely to make economic sense for many sheep producers in at-risk areas of the Intermountain West. Inclusion of risk aversion would also increase the economic attractiveness of a KV vaccine for producers in areas with outbreak intervals longer than 5 years. We do not attempt to determine, however, how large an effect this would have to be to overcome the KV vaccine's predominantly negative expected annual net benefit for longer outbreak intervals.

AUTHOR CONTRIBUTIONS

TM: acquisition of the data, analysis and interpretation of data for the work, drafting the work and revising it critically for important intellectual content, and final approval of the version to be published. DP: conception and design of the work, interpretation of the data, revising the manuscript critically for important intellectual content, and final approval of the version to be published. JR: data analysis and interpretation, revising the manuscript critically for important intellectual content, and final approval of the version to be published. RJ and MJ: data acquisition, revising the data, and final approval of the version to be published. MM: conception of the work, data acquisition, revising the manuscript for critically important intellectual content, and final approval of the version to be published. All authors agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at http://journal.frontiersin.org/article/10.3389/fvets.2017.00166/full#supplementary-material.

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ORIGINAL RESEARCH
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Modeling the Costs of Postpartum Dysgalactia Syndrome and Locomotory Disorders on Sow Productivity and Replacement

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Postpartum dysgalactia syndrome (PPDS) and locomotory disorders are common health problems in sows. Previous research suggests that they can cause substantial losses, reduce sow welfare, and result in premature removal of the sow from the herd. However, economic consequences of PPDS and locomotory disorders have not been investigated thoroughly. The goal of this study was to examine economic losses caused by PPDS and locomotory disorders and their impacts on sow longevity. A stochastic dynamic programming model, which maximizes return on sow space unit and assesses sow replacement under several scenarios, was developed. The state variables were litter size, parity number, and sow's health status. The model describes changes in the production parameters such as the number of piglets born and piglet mortality. Herd data originating from commercial sow herds and from a research farm were used to parameterize the model. Sow longevity, health, and economic results are related to each other. Eliminating the risk of PPDS from the model increased the value of sow space unit by €279 when compared to the baseline scenario. Eliminating the risk of locomotory disorders increased value by €110. Results suggest that these estimates correspond to about €29.1 and €11.5 in economic costs per housed sow during her lifetime. The estimated magnitude of losses was €300–€470 per affected sow for PPDS and €290–€330 per affected sow for locomotory disorders. However, realistically speaking, not all of these costs are avoidable. Due to premature replacement associated with these two disorders, the average number of litters that the sow would deliver during her lifetime is decreased by about 0.1–0.4 litters depending on the scenario. We also observed that the optimal lifetime of a sow is not a fixed number, but it depends on her productivity level as well as health status. In general, a healthy sow could stay in the herd until she has produced 6–10 litters. Research is needed to understand the structures and interactions underlying health impairments, performance, replacement policies, and farm economics, and to provide pork producers with management recommendations.

Keywords: dynamic programming, economic loss, sows, post partum dysgalactia syndrome, locomotory disease, longevity, piglet mortality, litter size

INTRODUCTION

Citizens perceive animal health and welfare as important dimensions of animal production (1, 2). Also from the producers' perspective, they are very important issues because production diseases in pigs can cause substantial losses [e.g., Ref. (3, 4)]. Diseases alter appetite, feed digestibility, impair the utilization of nutrients, and affect respiratory efficiency (5). Thereafter, health disorders typically continue to harm productivity of the affected animals in ways extending beyond the known pathological effects, potentially for a long time even after having been successfully treated.

Increased mortality and premature removal of sows from the herd have been studied widely (6–8), but relative to the overall effect of diseases in sow populations, they represent only a small proportion. At the herd level, fertility and productivity of sows as well as the quality of piglets are typically altered, and thereby, herd output and renewal potential is impaired. Consequently, involuntary herd turnover is increased, planned genetic progress deteriorated, and parity profile and overall performance of the herd adversely affected (9). Reduced sow longevity has also economic impacts (10). If an increased disease incidence leads to too high use of antimicrobial drugs, it can also be economically costly to the producer (11).

A number of studies have investigated the dynamics of sow herds, integrating directly observable, consistently and coherently reported information, by using data and records obtained for instance from farm production monitoring software (12–14). Simultaneously, economically costly outbreaks of some diseases, such as PRRS [e.g., Ref. (15, 16)] or *Actinobacillus Pleuropneumoniae* [e.g., Ref. (17)], have received attention. However, research on disorders of sows that cause less obvious losses to production and economics is scarce (18).

In this study, we focus on postpartum dysgalactia syndrome (PPDS) and locomotory disorders, which are common health problems occurring in sows. These diseases can cause productivity losses, elevated mortality, treatment costs, and premature sow removal from the herd [e.g., Ref. (19, 20)]. Furthermore, they have important welfare implications (20). However, there is limited research on the economic consequences of these two diseases in sows (4).

Postpartum dysgalactia syndrome and locomotory disorders influence sow longevity, which leads to economic losses [e.g., Ref. (21)]. For example, the costs of locomotory disorders in sows can range from a few dozens of euros up to €180 € per lame sow [e.g., Ref. (18, 22, 23)]. Wallgren et al. (22) estimated the cost of mastitis in sows in a median case at €95 per sow and substantially higher costs in the most severe cases, which were likely PPDS. Stalder et al. (24) reported that 21–35% of sows are removed from the herd due to reproductive failures, which include PPDS, and that 9–15% of sows are removed due to locomotory disorders. Regarding removal, a sow may be culled involuntarily due to the sow not recovering from a disease, or voluntarily due to poor productive performance stemming from the disease.

Because economic losses due to these two disorders are related to longevity, a well-designed sow replacement protocol is of vital importance to producers. The challenge, from the modeling perspective, is to identify important factors in the system, e.g., parity, reproductive efficiency, and frailty indicators, and incorporate them robustly in to the model. From a decision-making viewpoint, a major challenge is to account for the uncertainty and variation, especially in litter size. From several perspectives, there is a need for improved understanding of the links between animal health, productivity, sow removal, and economics.

This study contributes to the literature on the economic importance and sow removal implications of PPDS and locomotory disorders. The aims of this study are to: (1) assess economic burden of two common diseases in sows, namely PPDS and locomotory disorders and (2) examine parity and sow removal from the herd. We develop a numerical optimization model that simulates the production cycle of a sow and evaluates the replacement decision (i.e., removing a sow from the herd by culling and replacing her with a pregnant gilt).

MATERIALS AND METHODS

Diseases Studied

Postpartum dysgalactia syndrome affects both the sow and her litter. It occurs most commonly within the first 3 days after farrowing. Insufficient milk production is the most important symptom. Mastitis with or without total agalactia, oedema of the mammary gland, vaginal discharge, coprostasis, hyperthermia, apathy, and inappetence can also be observed. Although sows often show no clear symptoms at an early stage, the disease can be diagnosed by observing the piglets; PPDS is a primary cause for neonatal problems such as diarrhea, crushing, inanition, and poor growth [see, e.g., Ref. (19, 25–28)]. The phenomenon is sometimes referred to as problem litters.

Postpartum dysgalactia syndrome is stated to be the most common disease complex of sows after parturition [e.g., Ref. (29)]. Its etiologies and signs are numerous, and the dominant representation of this disease complex varies from herd to herd. Diagnostics, register keeping, and treatment differ greatly between herds as well as between reported studies. Thus, within and between herd, prevalence estimates are problematic to compare. In Belgium, 34% of herds reported having PPDS-related problems during the previous year (30). Herd-level estimates ranged from 1.1 to 37.2% (28). Average herd level PPDS incidence is approximately 13% (28, 31–35). However, very early lactation failure may affect 100% of sows in a farrowing group.

Locomotory disorders are painful conditions that alter swine physiology and behavior. They comprise variety of conditions, such as osteochondrosis, arthrosis, arthritis, leg weaknesses, paralysis, and foot or leg injuries, infections, and fractures in sows. Locomotory problems are prevalent conditions, but their clinical definitions, stage at which they are identified, and how they are treated vary greatly. Although literature has identified risk factors for leg disorders [e.g., Ref. (36)], locomotory problems are often not recognized early enough to make a successful intervention. Specific diagnosis would often require the use of different diagnostic methods such as radiography of bones and joints or bacteriology of joint fluid.

Sows suffering from locomotory problems are prone to impaired performance: they have longer lying times and are likely to have decreased appetite compared to their sound counterparts. Several studies have reported prevalences of locomotion, leg, and claw-related problems. An average of 10% lameness prevalence has been observed; however, this varies greatly between studies and among herds within the same study (20). Locomotory disorders, like PPDS, influence sow longevity [e.g., Ref. (37)].

Dynamic Programming Model of a Farrowing Farm

Objective Function

Piglet production is modeled with a stochastic dynamic programming model partly similar to the Hierarchic Markov Process model in Kristensen and Søllested (13). One benefit of dynamic programming is that it can take into account the value of information when it arrives, and its impacts on decisions. The assumed objective of a farrowing farm is to maximize net returns to a sow space unit by optimizing the replacement decision (the removal of a sow by culling, followed by the purchase of pregnant gilt). Sow space unit refers to the housing capacity that a sow requires during the production cycle.

The model accounts for the most important events in the productive life of a sow and its piglets. Replacement decisions are solved, and corresponding returns simulated, by state of nature, which represents observable characteristics of a sow. Parity number, piglet yield, and occurrence of a disease are used as the state variables. Uncertainty about sow performance is taken into account because exact piglet yield in the future is unknown when the producer decides on removal. By contrast, the mean and variance of biological parameters such as piglet yield are assumed to be known. The model optimizes the replacement decision on the condition that sufficient production capacity is allocated to each production stage. Hence, this maximized variable is return on investment given a specific production technology. Cost of capacity (i.e., fixed costs) is included in the model as a time-constant factor. Fixed costs are needed to make different production stages consistent, but they do not impact the optimal timing of replacement.

The Bellman equation (38) for this problem is of the form:

$$\begin{aligned} V_t(\mathbf{x_t}) &= \max_{u_t}\left\{R_{t,\text{sow}}(\mathbf{x_t},u_t)+\beta E(V_{t+1}(\mathbf{x_{t+1}}))\right\}, t=1,\ldots,\infty \text{ and where} \\ \mathbf{x_t} &= \{x_{t,\text{prices}}, x_{t,\text{disease}}, x_{t,\text{parity}}, x_{t,\text{litter}}\} \\ \text{subject to: } x_{t,\text{disease}} &= \{x_{t,\text{PPDS}}, x_{t,\text{leg}}, x_{t,\text{other}}\} \\ &= \Pr_{\text{disease}}(x_{t,\text{yield}}, x_{t,\text{parity}}) \\ x_{t+1,\text{litter}} &= g(x_{t,\text{parity}}, x_{t,\text{litter}}, u_t, \varepsilon_y) \\ x_{t+1,\text{parity}} &= q(x_{t,\text{disease}}, x_{t,\text{parity}}, x_{t,\text{litter}}, u_t) \\ &\mathbf{x_t} \text{ and } V_\infty(\mathbf{x_\infty}) \text{ are given,} \end{aligned} \tag{1}$$

where t is a time index measuring the number of farrowings elapsed from the start of production in the sow house; x_t is the state vector where $x_{t,\text{prices}}$, $x_{t,\text{disease}}$, $x_{t,\text{parity}}$, and $x_{t,\text{litter}}$ represent state variables for time-constant market prices, currently observed disease symptoms, currently observed parity number (1 = first farrowing, 2 = second farrowing, etc.) and currently observed litter size (i.e., total number of born piglets in the current parity) in period t, respectively; $x_{t,\text{disease}}$ refers to the occurrence of any of the relevant diseases (PPDS, locomotory disorders, other disorders) in the sow; $V_t(\mathbf{x_t})$ is the value function (i.e., the maximized value of a capacity unit as a function of the state variable) in time period t; $R_{t,\text{sow}}$ is a one-period returns function for time period t; u_t is the control variable; β is discount factor; $E(.)$ is an expectations operator applied on the term inside brackets; $V_{t+1}(\mathbf{x_{t+1}})$ is a value function at period $t + 1$; g is a transition equation governing the evolution of piglet yield over time as a function of state variables and control policy; q is a transition equation governing the evolution of parity number as a function of other state variables and control policy; $x_{t,\text{PPDS}}$ refers to the sow suffering from PPDS; $x_{t,\text{leg}}$ refers to the sow suffering from locomotory disorders; $x_{t,\text{other}}$ refers to the sow suffering from disease any other than PPDS or locomotory disorders;[1] $\Pr_{\text{disease}}$ is the probability of observing a disease in a sow during the current parity; and ε_y is a parameter indicating variation related to change in the litter size between successive parities.

The equations used in the model are specified in detail below. Transition equations for litter size and parity number have a controllable part that depends on the control variable, autonomous part that is realized deterministically, and a random part that is exogenous. In the model, we characterize how major events (**Figures 1** and **2**) affect cash flows, costs or revenues, during a farrowing cycle, and thus produce information needed to estimate one-period cash flows.

Control Variable and Parity Transition Equation

The control variable u_t can take on one of two values {0,1}, where 0 refers to not replacing the current sow after the current parity, and 1 refers to replacing the animal with a pregnant gilt. Hence, the endogenous replacement u is applicable to cases where exogenous replacement will not take place. Exogeneous replacement occurs with probability $\Pr_{\text{cull}}$, which is a function of parity, litter size, and sow's health status.

[1] Other disorders were not modeled explicitly but they were included in the model for consistency.

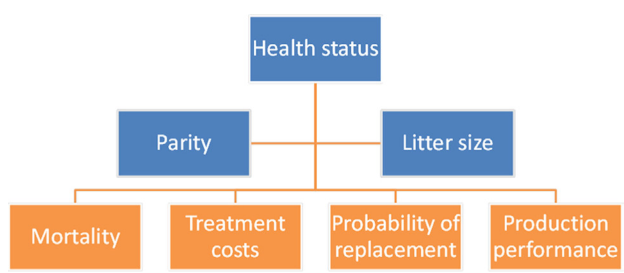

FIGURE 1 | State variables (in blue) influence economic and physical performance parameters (in orange) of a sow in the dynamic programming model.

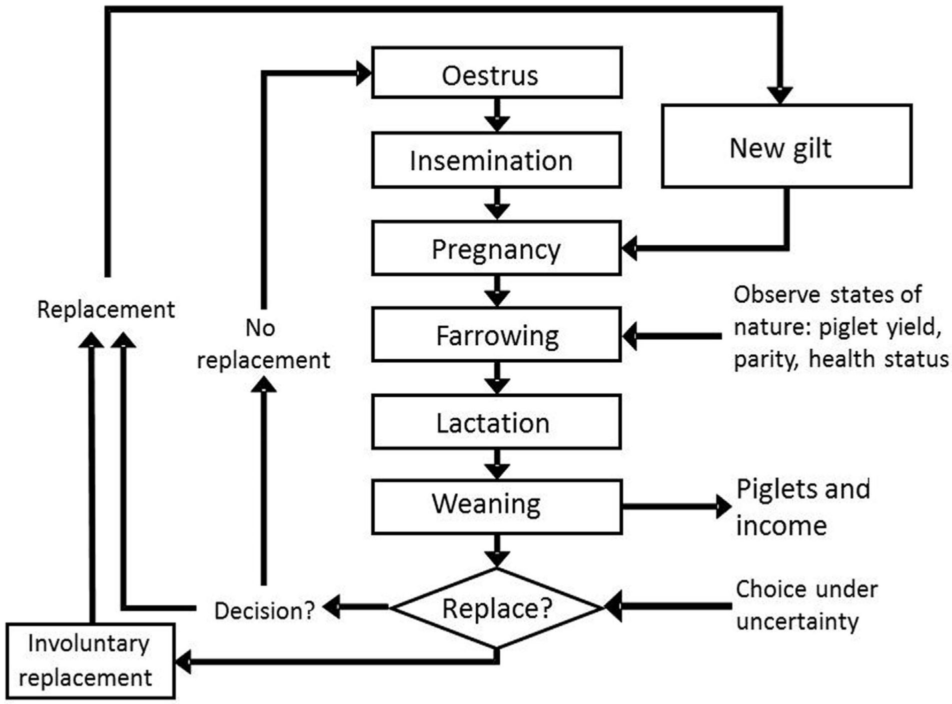

FIGURE 2 | The production cycle of a sow and cash flows (revenues, costs) associated with these events, as simulated in the dynamic programming model.

The transition equation for parity number is presented below in Eq. 2. In cases where the sow is not replaced, the parity number increases by one between successive farrowings. In cases where the sow dies or is culled due to disease, poor performance, or other reason, the parity number after the removal is set at one because the replacement animal is a gilt:

$$x_{t+1,\text{parity}} = q(x_{t,\text{disease}}, x_{t,\text{parity}}, x_{t,\text{litter}}, u_t) = \begin{cases} x_{t,\text{parity}} + 1 & \text{if sow is not removed,} \\ 1 & \text{if sow is removed} \end{cases} \quad (2)$$

The probability of removing the sow for exogenous reason, $\Pr_{\text{cull}}$, is parameterized as follows:

$$\begin{aligned} \Pr_{\text{cull}}(x_{t,\text{disease}}, x_{t,\text{parity}}, x_{t,\text{litter}}) \\ = \text{Probit}\begin{pmatrix} -0.608 - 0.041(x_{t,\text{parity}} \mid 1) - 0.111 x_{t,\text{parity}} + 0.020 x_{t,\text{parity}}^2 \\ -0.045 \min(x_{t,\text{parity}} - x_{t,\text{parity}}^*, 5) \\ +0.005 \min(x_{t,\text{parity}} - x_{t,\text{parity}}^*, 5)^2 \\ +1.214\,\text{SBM}(x_{t,\text{disease}}, x_{t,\text{parity}}, x_{t,\text{litter}}) \\ +0.360\,\text{SBM}(x_{t,\text{disease}}, x_{t,\text{parity}}, x_{t,\text{litter}})^2 \\ +0.980\,\text{PM}(x_{t,\text{disease}}, x_{t,\text{parity}}, x_{t,\text{litter}}) \\ +0.520\,\text{PM}(x_{t,\text{disease}}, x_{t,\text{parity}}, x_{t,\text{litter}})^2 \end{pmatrix} \\ -0.370 x_{t,\text{disease}} + Z(x_{t,\text{parity}}). \end{aligned} \quad (3)$$

where SBM refers to the proportion (%) of sow's born piglets in parity $x_{t,\text{parity}}$ that die neonatal or perinatal; PM is the proportion of born piglets that die between farrowing and weaning. Operator "min" selects the smallest element inside the parenthesis. We restrict this element to a maximum of five, and the variable $x_{t,\text{parity}}^*$ refers to the number of piglets born to an average sow in the herd in a given parity (more specifically, when no "sample selection" of sows would have occurred due to removing poorly performing sows in the previous parities). Therefore, $x_{t,\text{parity}} - x_{t,\text{parity}}^*$ refers to how much a sow's current (observed) litter size deviates from the expected litter size of an average sow that has farrowed a given number of times. $Z(x_{t,\text{parity}})$ is a calibration parameter that ensures the best fit for the combination of the two datasets used. For the first three parities, it has an average value of 0.12; thereafter decreasing by about 0.05 per parity. $\Pr_{\text{cull}}$ is restricted to have a minimum value of zero and a maximum value of one.

Data Sources

The Probit model we use is originate from Niemi et al. (39), which is based on a dataset obtained from the Finnish Animal Breeding Association (Faba), a former animal breeding cooperative in Finland. This source provided animal-level data on the productivity and genetic background of sows from 31,949 litters born in 2002. $\Pr_{\text{cull}}$ was reported for an animal of average genetic merit that was housed by a farm with the parameters similar to the sample average. Hence, our model focuses on a typical sow on a typical herd.

Beyond the Probit within Eq. 3, model was calibrated using our data collected from commercial sow herds by University of Helsinki coauthors. These data originated from 40 herds and covered 18,753 sows in the herds in 2014. We used these data to calibrate litter sizes and primiparous sow removal rate to 2014 levels. Therefore, the parameter values in our entire model are based on joint information from two datasets.

These datasets did not provide sufficient animal-level follow-up information on PPDS and locomotory disorders over several parities. Therefore, we obtained information on how the health of a sow impacts sow removal and litter size from the herd database of a former pig research station, which had been operated by Natural Resources Institute Finland (Luke) at Hyvinkää, Finland. The Luke dataset comprises 871 sows born between 1998 and 2012, and measures 2,568 litters. For each sow, the data included performance data (litter size, number of litter, etc.) and records of production diseases, veterinary and medical treatments, and exit dates with removal destination and general reasons. The effect of health disorders on productivity at various parities was obtained from the data including sows treated or not treated with antimicrobials, pain killers, or both. The data included no cases of observed production disease without treatment. For each sow, the time of entering the herd, the time of removal, and the time spent in the herd, were considered. Parameter −0.370 in Eq. 3 above is an adjustment factor that quantifies how disease in the sow contributed to removal.

Transition Equation for Litter Size

Litter size (i.e., the total number of piglets born, either alive or stillborn) is a random variable whose evolution over successive parities is modeled as a stochastic process based on the commercial herds datasets:

$$x_{t+1,\text{litter}} = \begin{cases} -6.118 + 0.219x_{t,\text{litter}} + 0.700x_{t,\text{parity}} - 0.100x^2_{t,parity} - \\ 0.765\ \text{SBM} + 0.308\text{PMT} - 0.781N_{t,\text{litter}} + \varepsilon_{\text{litter}} & \text{if } x_{t+1,\text{litter}} > 1 \\ 12.37 + \varepsilon_{\text{primiparous}} & \text{if } x_{t+1,\text{litter}} = 1 \end{cases}, \quad (4)$$

where PMT is the ratio of piglets born alive to the total number of piglets born; $N_{t,\text{litter}}$ is a factor used to adjust expected litter size to the currently prevailing level; $\varepsilon_{\text{litter}}$ is unexplained variation in litter size (mean = 0, SD = 3.025 piglets) for multiparous sows, and $\varepsilon_{\text{primiparous}}$ is variation in litter size (mean = 0, SD = 2.606) for primiparous sows. The factor $0.219x_{t,\text{litter}}$ refers to the repeatability of deviation of litter size when compared to the expected litter size had sample selection (i.e., removal of less productive sows) not occurred. In addition, 1.41% mortality for sows per farrowing cycle is assumed. The probability distribution for litter size of primiparous sows given in **Figure 3** is based on the commercial herds datasets.

Hierarchical Modeling of Diseases in Pigs

Interactions between disease incidence and litter size and piglet mortality are modeled hierarchically based on the Luke data. For a given current litter size, the likelihood of a sow suffering from a disease is first adjusted according to Eqs 5–7 below. That is, the model first determines litter size, and then which individuals are suffering from disease. Next, piglet mortality (Eq. 8) and sow removal rates (Eqs 2 and 3) are determined as a function of litter size and disease. Hence, disease influences litter size through model dynamics presented in Eqs 2–4.

Culling Rates for Treated and Untreated Sows

To parametrize the impacts of PPDS and locomotory disorders in sows, we use the Luke data as described in more detail here. The dataset provides detailed health records for each sow. During parities 1–4, the most common reasons for treating a sow were PPDS[2] (26–40% of treatments) and locomotory disorders (23–31%). During parities 5–9, locomotory disorders were the most common reasons for treatment (32–100%). Percentage of sows treated was highest at the first parity (18%), decreasing to 13–16% at parities 2–5, and to 11% or less at parities 6–11.

In the first parity, sows with reported disease and treatment farrowed fewer piglets compared to healthy and thus untreated sows (**Table 1**). However, at parities 2–4, no major differences were found. During parities 1–5, treated sows had 0.1–0.6 more

[2]We considered the udder-related dysfunctions that occur during the postpartum period from day 0 to 4 following parturition.

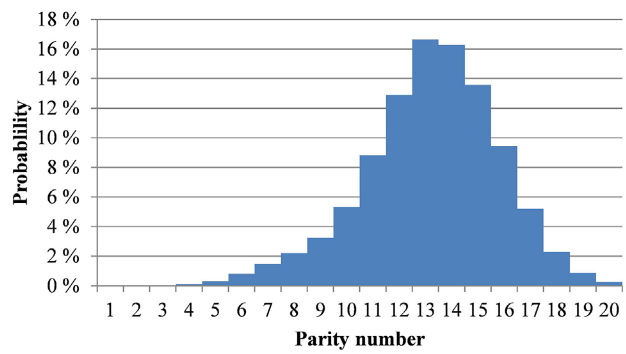

FIGURE 3 | Probability distribution of litter size assumed in the dynamic programming model for primiparous sows.

TABLE 1 | The number of liveborn and stillborn piglets (mean) by parity for sows treated healthy and thus untreated.

Parity number	Number of sows		Liveborn		Stillborn	
	Untreated	Treated	Untreated	Treated	Untreated	Treated
1	645	140	10.2	8.5	1.0	1.3
2	514	74	10.6	11.1	0.9	1.2
3	373	70	11.6	11.5	1.1	1.5
4	230	38	12.4	12.8	1.1	1.2
5	159	24	12.4	11.9	1.3	2.0
6	118	8	12.3	10.5	1.6	1.3
7	78	10	12.4	10.9	1.5	2.1
8	43	4	12.0	13.3	2.3	1.0
9	17	2	11.8	11.0	1.3	1.5
10	7	0	12.3	n/a	1.7	n/a
11	1	2	13.0	12.0	2.0	4.5

Data are from a research at Hyvinkää, Finland.

stillborn piglets than untreated sows. After the fifth parity, treated sows produced fewer piglets than untreated sows.

In the first parity, the number of piglets born alive was statistically different for treated versus untreated sows at the risk level of 0.01 (t-test, $p = 0.000$). However, the difference in number of stillborn piglets at the first parity was less evident ($p = 0.070$). During parities 2–4, no statistical significances were found at the 0.05 risk level. At parity 5 or thereafter, there were too few sows to permit statistical analysis.

After the first parity, 25% of sows in this dataset were removed from the herd (**Table 2**). Of these primiparous sows, 43% were reported to have been suffered from a production disease and been treated. As parity number increased, the percentage of removal increased and the percentage of treated sows among them decreased. During parities 1–5, the average number of piglets born alive was 0.9 higher (and the number of stillborn piglets was 0.3 lower) for sows remaining in production than for removed sows. Hence, piglet yield may have been a factor in research farm's decision to replace a sow. Treatment rate did not seem to increase as parity number increased. On the contrary, the highest *overall* percentage of treated sows and removal rate after treatment was found at the first parity.

Based on the data available for each disease, the probability of occurrence for PPDS, locomotory disorder, and any other disorder is determined as a function of litter size (total number of piglets born) and parity number:

$$\Pr(x_{t,\text{PPDS}}) = 0.073 - 0.012x_{t,\text{parity}} - 0.047(x_{t,\text{parity}} | = 1) + 0.056(x_{t,\text{parity}} | \geq 9) + 0.004x_{t,\text{litter}} \quad (5)$$

$$\Pr(x_{t,\text{leg}}) = 0.068 - 0.04x_{t,\text{parity}} + 0.085(x_{t,\text{parity}} | \geq 9) - 0.002x_{t,\text{litter}} \quad (6)$$

$$\Pr(x_{t,\text{other}}) = 0.073 + 0.003x_{t,\text{parity}} + 0.029(x_{t,\text{parity}} | = 1), \quad (7)$$

where Pr(.) refers to the probability of occurrence of the disease of interest and given the parity number and litter. Note that some parameters are multiplied by dummy variables that take a value of 1 only for given parity numbers (i.e., they are conditional).

TABLE 2 | Shares of removed and remaining sows in a research farm herd, by parity, and shares of removed sows by veterinary treatment.

Parity number	Number of litters in the data	Remaining sows, %	Removed sows, %	Removed after treatment, %	
				No	Yes
1	790	75	25	57	43
2	589	76	24	72	28
3	444	61	39	71	29
4	268	68	32	77	23
5	183	67	33	75	25
6	126	70	30	84	16
7	88	52	48	79	21
8	47	38	62	83	17
9	19	37	63	83	17
10	7	43	57	100	0
11	3	0	100	33	67

Piglet Mortality

Neonatal and perinatal piglet mortality (SBM) as well as piglet mortality after birth until weaning (PM) are determined as follows:

$$\begin{aligned} \text{SBM} = 0.072 &+ 0.011\ln(x_{t,\text{parity}}) \\ &+ 0.103\Pr(x_{t,\text{PPDS}} \mid x_{t,\text{parity}} = 1) \\ &+ 0.019\Pr(x_{t,\text{PPDS}} \mid x_{t,\text{parity}} |> 1) \\ &+ 0.073\Pr(x_{t,\text{legs}} \mid x_{t,\text{parity}} = 1) + 0.094\Pr(x_{t,\text{other}}), \end{aligned} \quad (8)$$

$$\text{PM} = 0.096 + 0.018\ln(x_{t,\text{parity}}). \quad (9)$$

Pr(.) is defined separately for litters of primiparous and multiparous sows as are mortality rates. The probability of locomotory disorders is defined only for the first parity because elevated mortality only occurred for the litters of primiparous sows. The probability that any other disorder is observed is defined the same for any parity. Finally, PM is defined as a proportion of the total number of piglets born (i.e., it is based on the state variable and not on piglets born alive). Parameter values for the impacts of disease on piglet mortality are calculated from the Luke's research farm dataset as the difference between mortality rates among treated and untreated sows in the same parity. Litter-size-dependent piglet mortality is estimated using a combination of the two datasets. Piglet mortality after weaning is assumed to be fixed at 3.2%.

Other Physical Parameters

Other parameters are based on information collected from farms and relevant literature. Pregnancy is assumed to last for 116 days. Piglets are assumed to be weaned at the age of 28 days (9.6 kg) and sold for fattening at the age of 67 days (30 kg). A sow is assumed to return to estrus 1 week after weaning. If an insemination is unsuccessful (as 20% are assumed to be), the time interval between successive parities is increased. These sows must be re-inseminated, when they return to estrus 3 weeks later. A sow may be serviced a maximum of three times before it is removed from the herd due to infertility (7.5% of sows).

Piglets and sows were assumed to be fed according to the Finnish feeding recommendations (40). Working time needed to take care of the sows and piglets were obtained from Parviainen (41) and the space allowance (square meters) per piglet and sows was determined according to recommendations by MMM (42).

Price Parameters and One-Period Returns

Consistent with our model's recursive structure, the cash flow of a piglet producing farm is described by one-period revenues and costs, which are obtained over time and separately for each time period (see Eq. 1). One-period returns depend on the state of nature, policy chosen, and economic parameters. More specifically, they take into account revenue from selling piglets, and expenses related to feeds, insemination, sow replacement, labor, and veterinary services. The total cost of producing piglets includes fixed costs, although they do not affect the model's solution.

Table 3 describes the price parameters used in the model. These are based on national statistics and information acquired from commercial farms.

TABLE 3 | Price parameters used in the dynamic programming model.

Parameter	Value	Unit
Number of piglets born per primiparous sows	13.24	Piglets/litter
Gestation feed	17.42	€/1,000 MJ NE
Lactation feed	21.19	€/1,000 MJ NE
Piglet feed	39.35	€/1,000 MJ NE
Price of labor	16.00	€/h
Price of gilt	350.00	€/gilt
Price of insemination dose	25.00	€/serving
Value of culled sow	108.00	€/sow
Price of piglet (30 kg)	55.29	€/piglet
Cost of veterinary treatment (labor, medicine)	30.00	€/treatment
Fixed housing costs	351.00	€/m^2
Discount rate	6%	Per annum
Maintenance costs of housing	1%	Of house value
Overhead costs	4%	Per other costs

MJ NE, mega joules net energy.

Data regarding the cost of treatment, treatment efficacy, or the cost effectiveness are not readily available. Direct costs of treatments (veterinarian visits, procedures, and medicines) are estimated based on veterinary inspection visits, which occur six times a year, cost of medication, and increased labor. This labor is estimated as an average cost per task involved in treating an animal with either of the diseases, including veterinary care, labor to conduct the diagnosis, and administration of the treatment. Other cost consequences are determined by the equations presented in the previous sections.

A policy iteration method is used to solve the stochastic dynamic programming model [e.g., Ref. (43)]. Because litter size, piglet mortality, and parity number are stochastic factors that show covariation, Choleski factor decomposition is used when simulating these variables. Correlation between various biological parameters of the sow are based on the two datasets. Where a parameter is unavailable, we select a value based on results reported by Serenius et al. (44). The model was programmed in Matlab R2014b (8.4.0150421; The MathWorks, Inc., Natick, MA, USA).

Scenarios

The following scenarios are simulated first and, thereafter, results are compared to the baseline scenario.

(1) The baseline scenario where the model is parametrized as described in Section "Dynamic Programming Model of a Farrowing Farm."
(2) The incidence of PPDS is reduced by 50% from the baseline scenario.
(3) The incidence of PPDS is set at 0 (reduced by 100% from the baseline scenario).
(4) The incidence of locomotory disorders is reduced by 50% from the baseline scenario.
(5) The incidence of locomotory disorders is set at 0 (reduced by 100% from the baseline scenario).
(6) The incidence of PPDS and locomotory disorders are set at 0.
(7) The probability of removing the sow (Pr_{cull}) is decreased by 0.1 (10%) from the baseline scenario.

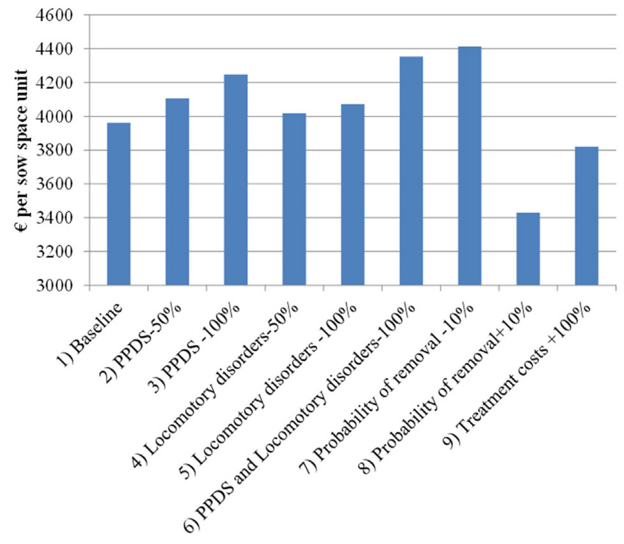

FIGURE 4 | Return on fixed costs (€ per sow space unit) in the scenarios simulated by the dynamic programming model. PPDS, postpartum dysgalactia syndrome.

(8) The probability of removing the sow (Pr_{cull}) is increased by 0.1 (10%) from the baseline scenario.
(9) Treatment costs of sows suffering from either disease is doubled from the baseline scenario.

In addition, a sensitivity analysis on the economic impacts of diseases in response to a farm's average sow replacement rate is conducted. This is done by simulating each scenario (1 through 9) with the probability of removal increased by reducing the calibration factor $Z(x_{t,\text{parity}})$ by 0.06 points with comparison to Eq. 3. This allows us to examine the economic consequences of disorders in a herd where sow longevity is generally poorer than in the standard simulation. This may be relevant because sow replacement rates vary from herd to herd, and the initial replacement rate is expected to influence economic losses caused by various scenarios.

RESULTS

Value of Sow Space Unit

Figure 4 shows the return on fixed costs (or return over variable costs) for each scenario, which is measured as the value function in the first period minus the fixed costs. In the baseline scenario, it is simulated to be €3,962 per sow space unit (over entire lifetime of that unit), which on average corresponds to €12 per piglet or about €119 per litter. These estimates take into account revenues and variable costs from all sows kept at the sow space unit currently or in the future. However, after accounting for fixed costs, the simulated net present value (i.e., all discounted revenues minus all discounted costs) of the sow space unit is substantially lower. After subtracting fixed costs, the net present value in the baseline scenario falls to €313 per sow space unit.

Eliminating PPDS from the model increases the value of sow space unit by €279 (7% of baseline return on fixed cost) and eliminating locomotory disorders increases the value by €110 (3% of the baseline). This corresponds to about €29.1 and €11.5 per housed sow during her lifetime. Focusing on ill sows, PPDS is estimated to lead to losses of €300–€470 and locomotory disorders are estimated to lead to losses of €290–€330 per affected sow. Hence, for an average-sized herd in the 2014 dataset (469 sows per herd), the losses could be about €11,000 annually. Increasing the likelihood of a sow's removal by 0.1 (+10%) decreases the value function by €546; conversely, decreasing it by 0.1 (−10%) increases the value function by €462 per sow space unit. Finally, doubling the treatment costs decreases the value function by €142 per sow space unit when compared to the baseline scenario. Doubling treatment costs for all diseases results in losses, which are close to 30% of the losses estimated to be caused by PPDS and locomotory disorders.

Recall that, for the sensitivity analysis, the model was run with the similar parameter values as above with the exception that the sow replacement rate was increased by 0.06 points by adjusting the calibration factor. With this higher probability of removal, scenarios 1 through 9 generate 2–12% larger impacts on the value function compared to the standard simulation (i.e., the magnitude of the difference between the baseline scenario and other scenarios is larger in **Figure 5** than in **Figure 4**). For instance, the costs due to PPDS increase from €279 to €294 per sow space unit and losses due to locomotory disorders increased from €110 to €120 per sow space unit. Therefore, herds with a higher sow replacement rate appear to suffer more from diseases than herds with a lower sow replacement rate.

Likelihood of Replacement

Table 4 summarizes, from our simulation results, the likelihood of replacement given a sow's parity and litter size, regardless of disease status. The table shows that a sow is typically replaced after the seventh or eighth parity even if it would otherwise be in good condition. This is because the expected productivity of a primiparous sow is sufficiently high to justify the current sow's removal. Although a sow producing smaller litters has an elevated likelihood of replacement, a smaller litter as such does not necessarily lead to removal.

Results from scenario 7 reveal that a 0.1 (−10%) decrease in Pr_{cull} decreases the likelihood of replacement as expected by definition, but also results in more rapid replacement of sows that produce the smallest litters, about one parity earlier than in the baseline scenario. This is because scenario 7 increases expected productivity of the subsequent sow compared to poorly yielding current sow and, therefore, makes it more profitable to replace poorly yielding sows. Moreover, increasing profitability in general shortens the production cycle in dynamic programming models. A qualitatively similar result is obtained if both PPDS and locomotory diseases are assumed to be absent. An opposite but smaller impact is obtained when Pr_{cull} is increased by 0.1 (+10%). The removal of disease results in the same incentive to remove low-yielding sows sooner.

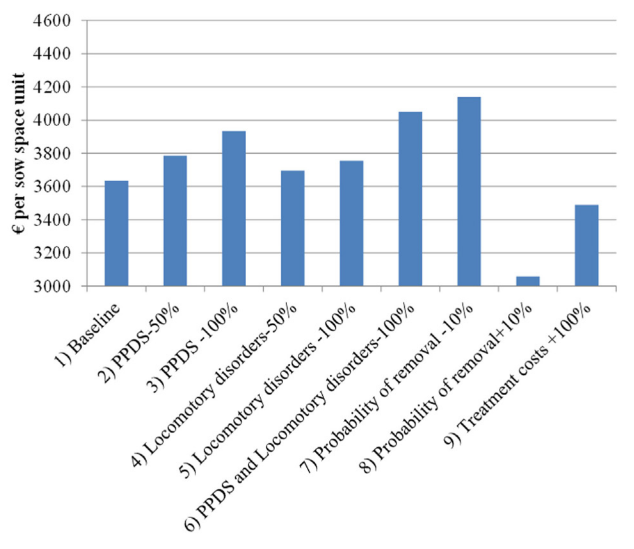

FIGURE 5 | Return on fixed costs (€ per sow space unit) in the sensitivity analysis scenarios simulated by the dynamic programming model. PPDS, postpartum dysgalactia syndrome.

Piglet Yields and Longevity

Table 5 summarizes, from our simulation results, lifetime piglet yields and expected number of litters produced per sow. In the baseline scenario, on average, 9.8 piglets per litter are sold and the average number of litters a sow produces is 3.5. Eliminating

TABLE 4 | The likelihood of replacing a sow, by parity and litter size, as simulated by the dynamic programming model.

		Parity number								
		1	2	3	4	5	6	7	8	9
Litter size (total number of born piglets)	1	0.55	0.63	0.66	0.67	0.69	1.00	1.00	1.00	1.00
	2	0.51	0.58	0.61	0.62	0.64	1.00	1.00	1.00	1.00
	3	0.46	0.52	0.55	0.57	0.59	1.00	1.00	1.00	1.00
	4	0.42	0.48	0.50	0.52	0.54	0.56	1.00	1.00	1.00
	5	0.38	0.43	0.46	0.48	0.50	0.52	1.00	1.00	1.00
	6	0.35	0.39	0.41	0.43	0.45	0.48	1.00	1.00	1.00
	7	0.32	0.35	0.37	0.39	0.41	0.44	1.00	1.00	1.00
	8	0.29	0.32	0.34	0.36	0.38	0.41	1.00	1.00	1.00
	9	0.27	0.29	0.31	0.33	0.35	0.38	0.42	1.00	1.00
	10	0.26	0.27	0.28	0.30	0.32	0.36	0.40	1.00	1.00
	11	0.25	0.25	0.26	0.28	0.30	0.33	0.38	1.00	1.00
	12	0.24	0.24	0.24	0.26	0.28	0.32	0.37	1.00	1.00
	13	0.23	0.22	0.23	0.24	0.27	0.31	0.36	1.00	1.00
	14	0.23	0.22	0.22	0.24	0.26	0.30	0.35	1.00	1.00
	15	0.24	0.21	0.22	0.23	0.25	0.29	0.35	0.46	1.00
	16	0.24	0.21	0.21	0.23	0.25	0.29	0.35	0.46	1.00
	17	0.25	0.22	0.22	0.23	0.25	0.30	0.36	0.47	1.00
	18	0.26	0.22	0.22	0.23	0.26	0.31	0.37	0.48	1.00
		Color scale of likelihood								
		0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00

0 = no replacement, 1 = always replaced.

TABLE 5 | Lifetime piglet yield (number of weaned piglets and sold piglets) per sow, and expected number of litters produced per sow, according to the dynamic programming model for the analyzed standard simulation scenarios and sensitivity analysis scenarios.

		Standard simulation			Sensitivity analysis		
		Piglets sold	**Piglets weaned**	**Number of litters**	**Piglets sold**	**Piglets weaned**	**Number of litters**
(1)	Baseline	34.0	35.1	3.48	29.1	30.1	2.90
(2)	PPDS −50%	35.4	36.6	3.62	30.2	31.2	3.00
(3)	PPDS −100%	36.8	38.1	3.76	31.4	32.4	3.10
(4)	Locomotory disorders −50%	34.6	35.8	3.54	29.6	30.6	3.00
(5)	Locomotory disorders −100%	35.2	36.4	3.61	30.1	31.1	3.00
(6)	PPDS, locomotory disorders −100%	38.1	39.3	3.88	32.5	33.5	3.30
(7)	Probability of removal − 10%	44.2	45.7	4.56	37.3	38.6	3.80
(8)	Probability of removal + 10%	26.8	27.7	2.72	23.3	24.1	2.30
(9)	Treatment costs doubled	34.1	35.2	3.49	29.1	30.1	2.90

PPDS, postpartum dysgalactia syndrome.
All percentage changes in the scenarios refer to a change from the baseline scenario.

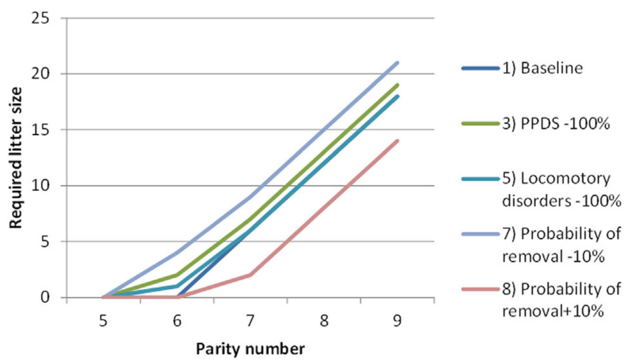

FIGURE 6 | The minimum litter size (by parity number) that a sow must to exceed in order to remain in the herd, according to five scenarios simulated by the dynamic programming model. PPDS, postpartum dysgalactia syndrome.

either PPDS or locomotory disorders from the model (scenarios 3 or 5) yields 0.1–0.3 more litters and 1–3 more piglets sold during the sow's lifetime. However, this result was constrained by the structure of the model. Scenario 7, in which the probability of removal was decreased by 0.1 (−10%) resulted in 1.1 litters higher lifetime production than the baseline scenario. Therefore, being able to reduce the removal rate would increase sows' lifetime productivity more substantially because then the change in removal rate applies to all sows. The removal rate can be reduced for instance, by sound and planned culling policy, which requires an in-depth understanding of herd characteristics, applying a combination of low culling rate and rigorous monitoring and health management in early parities, or by improving breeding policies and gilt selection.

Figure 6 illustrates, for a subset of scenarios, how large a litter would have to be in each parity for the sow to be replaced. For instance, according to the baseline scenario, a sow must produce at least six piglets in their seventh parity and at least 12 piglets in their eighth parity, or they will be replaced. However, in scenario 7, where the probability of removal is decreased by 0.1 (−10%), a larger number of piglets is required for the sow not to be replaced. In other words, although the longevity of the sow is improved, a larger litter must be produced for the sow to be kept in the herd as compared to the baseline scenario.

DISCUSSION

In this paper, we have examined the economic burden of two important and common disease complexes in sows, PPDS, and locomotory disorders with special attention to sow longevity. We have also examined the criteria to replace a sow by parity and litter size as identified using a numerical dynamic programming model.

We compared several scenarios associated with two health conditions. In summary, the results suggest that the losses due to the occurrence of PPDS and locomotory disorders for an average-sized herd in the 2014 dataset (469 sows per herd) could be about €11,000 annually. With 5–15% prevalence of the studied diseases in our dataset, the estimated losses per diseased sow could be €300–€470 for PPDS and €290–€330 for locomotory disorders. Further, the prevalence of these disorders as reported in the literature implies that the costs would be considerable at the country level. Expanding the perspective to national level shows that a rough estimate based on our calculations adds up to a total amount of €2 to €4 million in Finland annually. In comparison with the highly contagious diseases, which occur rarely but cause costly outbreaks (45–47), the one-time economic burden caused by PPDS and locomotory diseases is smaller. However, the constant presence and high incidence of PPDS and locomotory disorders make their overall costs likely larger than those of highly contagious diseases.

In comparison to published studies, our estimates are fairly high (4, 18, 22, 23). This may be due to several aspects, including differences in the assumed impacts of diseases on the removal rates, differences in piglet prices, and differences in the modeling approaches used.

Our results demonstrate that the optimal lifetime of a sow is not a fixed number, as Kristensen and Søllested (13) have already shown. Instead, it depends on several parameters such as litter size, piglet mortality, reproductive efficiency, and sow health. Hence, if someone suggests that it is optimal to remove a sow after a specific parity, one should explore first whether they are referring to an average optimal terminal parity. According to our results, it is optimal for a healthy sow to stay in the herd until at least sixth or seventh parity. Thereafter, it is optimal to remove the sows producing the smallest litters, but sows producing large litters might stay until their ninth or tenth parity.

When evaluating sow longevity, it is essential to pay attention to variation in parameters such as litter size, sow replacement rate, piglet mortality, and sow health. Sow productivity, especially litter size, can vary substantially from litter to litter, with important economic consequences. Yet, sows in their first three to five parities should not necessarily be removed due to a small litter size because litter size varies so much. However, some recent studies have suggested also the opposite, i.e., more intensive use of information regarding the first and second parity performance, when deciding to remove a sow [e.g., Ref. (48)]. Litter size could indeed play a more important role in sow removal if a producer is able to reduce the overall removal rates and improve sow health, because at a lower overall removal rate, the sow needs to produce larger litters to stay in the herd.

Our study design limits the generalizability of our results to individual farms. Disease-related parameter values in our model were collected from a small research farm with thorough record keeping and educated diagnostic abilities. Our results are estimated at the sow level and represent the distribution of outcomes at the herd level. Because the situation may vary from herd to herd, applying the results will require information on farm-specific factors. The information needed includes detailed data on animals and knowledge on the costs of treatment and treatment efficacy or cost-effectiveness, which are often unavailable.

The benefit of our approach, though, is that it can be used to conduct what-if-analyses. In this study, we showed that the elimination of PPDS and locomotory disorders has the potential to improve return on sow space unit and increase sow longevity. The animal disease literature has suggested potential measures to lower the incidence of these two diseases. These measures include, depending on the disease and risk factors present at the farm, gilt development, and selection, improvements in sows' nutrition and hygiene, quality of stockmanship, and flooring (28, 49–52). Although the diseases could in theory be fully eradicated, in practice, not all costs caused by the two diseases are avoidable. Preventive measures also incur costs. Hence, the potential to improve return on sow space unit is less than the estimated economic burden of the diseases. Our results can nevertheless motivate producers to consider taking actions. Investigating the economic rationale of these measures is beyond the scope of our study, but our model could be used in such an investigation, which has not been conducted thoroughly from an economic perspective.

Production diseases of sows are a challenging area for prevention, treatment, clinical research, and modeling as they produce substantial economic burden for the whole pork production chain at all levels and impairs welfare of individual animals. Given the lack of data currently available, rigorous studies are still needed to quantify this burden appropriately to and determine the best course for accurate diagnosis, treatment, and prevention strategies. Improved understanding of the costs related to diseases can help motivate the implementation of direct animal health interventions. Improving animal health offers a win–win opportunity to improve both the farm economic performance and animal welfare.

AUTHOR CONTRIBUTIONS

JN was the main responsible for this study. He contributed to all parts of the study and, especially, developed the model application in practice, undertook data analysis and initial drafting of the article, and contributed to in outlining the research focus and the idea of the article. PB collected literature on diseases in sows, information based on the 40 farms dataset and on the current level of productivity of sows farms, and to the discussion section of the article. SO analyzed data from the experimental farm used in the model and provided information to the manuscript. M-LS-A contributed the data, which were used to quantify litter size, piglet mortality, and sow replacement rates without a disease, and she contributed to planning of the initial dynamic model. MH supervised the project and contributed to planning the analyses and outlining the research focus and idea of the article. All authors contributed to preparing the article.

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Replacement Beef Cow Valuation under Data Availability Constraints

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Economists are often tasked with estimating the benefits or costs associated with livestock production losses; however, lack of available data or absence of consistent reporting can reduce the accuracy of these valuations. This work looks at three potential estimation techniques for determining the value for replacement beef cows with varying types of market data to proxy constrained data availability and discusses the potential margin of error for each technique. Oklahoma bred replacement cows are valued using hedonic pricing based on Oklahoma bred cow data—a best case scenario—vector error correction modeling (VECM) based on national cow sales data and cost of production (COP) based on just a representative enterprise budget and very limited sales data. Each method was then used to perform a within-sample forecast of 2016 January to December, and forecasts are compared with the 2016 monthly observed market prices in Oklahoma using the mean absolute percent error (MAPE). Hedonic pricing methods tend to overvalue for within-sample forecasting but performed best, as measured by MAPE for high quality cows. The VECM tended to undervalue cows but performed best for younger animals. COP performed well, compared with the more data intensive methods. Examining each method individually across eight representative replacement beef female types, the VECM forecast resulted in a MAPE under 10% for 33% of forecasted months, followed by hedonic pricing at 24% of the forecasted months and COP at 14% of the forecasted months for average quality beef females. For high quality females, the hedonic pricing method worked best producing a MAPE under 10% in 36% of the forecasted months followed by the COP method at 21% of months and the VECM at 14% of the forecasted months. These results suggested that livestock valuation method selection was not one-size-fits-all and may need to vary based not only on the data available but also on the characteristics (e.g., quality or age) of the livestock being valued.

Keywords: livestock valuation, data constraints, price forecasting, model comparison, bred cattle values

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INTRODUCTION

Livestock husbandry involves many production risks including disease, predators, and natural disasters. When such events occur on a large scale—as in the case of a large-scale natural disaster such as drought or blizzard or in the case of a multistate disease outbreak—the production losses have consequences beyond the farm gate, affecting local economies, associated industries such as processing, and consumers. Economists are often tasked with estimating the impacts associated with production shocks. Frequently, the first metric of impact estimated is the extent of death or reduced production and the subsequent financial losses to a livestock owner. These direct losses arise from death, abortion, or reduced productivity such as lower average daily gain or lower daily milk production. Ideally, valuation would be based on timely, comparable animal transaction data from an animal with similar type, age, and quality characteristics sold in the same regional cash market as the animal being valued. However, lack of available data or absence of consistent reporting reduces the efficacy of these valuations. Several factors limit the availability or usability of market data including market data accessibility, market reporting, market thinness,[1] and integrated or closed-system farming. The extent to which data are constrained affects the options available for livestock valuation.

Factors associated with market data accessibility are the more obvious limitations of livestock valuation. The traditional livestock market model, a centralized location in which substantial numbers of buyers and sellers meet face-to-face to trade livestock, is still common in many parts of the world. Bids are public knowledge, and transaction data provide information for both public and private users (1). Market data accessibility poses a challenge to those livestock producers in isolated areas. In such situations, little transaction data are available for livestock in outlying towns and villages. When transaction data are available, high costs of getting animals to a central market location affect loss estimate accuracy, particularly on livestock that are raised for local consumption and were never destined for a centralized market. Even when auction markets are accessible, not all markets record and maintain transaction data on a regular basis. In volatile market conditions, the infrequent reporting of transaction data raises questions of the timeframe that is appropriate for estimating livestock values.

The increasing use of alternative marketing arrangements in lieu of traditional livestock markets further complicates the issue of livestock valuation. Transactions in livestock auction markets may still be seen as the primary price discovery mechanism; however, a trend of reduced utilization of markets threatens the usefulness of traditional market transaction data for pricing. For example, Joseph et al. (2) found that the futures market played the greatest role in price discovery in the United States fed cattle market from 2001 to 2012. Mathews et al. (1) similarly found that price discovery in the cattle market from 2008 to 2014 was largely driven by the cattle futures market in the United States, while cash transactions in traditional markets played a smaller, but still significant, role. Other market streams include virtual or online auctions, private treaty sales, and forward contracting.

Fully integrated, farm-to-table companies may not estimate the value of their intermediate stage livestock. Instead these companies focus on the value of the final retail product and the impact on their financial bottom line. In the United States, the cash market for poultry has virtually disappeared (1). The swine industry in the United States also exhibits a large degree of integration, and live swine are sold in a cash market less frequently. Consequently, concern exists for the accessibility of cash market swine prices for price discovery (3). Concerns over thinning cash markets have been discussed in the market literature for some time, and increasing consolidation in all sectors mean this discussion is likely to continue into the future.

Cash market values may inadequately capture the role of livestock as a personal capital asset (4), the impact livestock have in community supported agriculture, and the importance of livestock in a local food system. For example, a cow can provide milk, progeny and draft power in her lifetime plus meat and hide at the end of her productive life. Further the value of genetic stock, or seedstock, includes intangible characteristics such as investment in genetic improvement (5) or reputation-value (6). Valuing a cow's loss with only her meat value at the market level will undervalue her role to a farm or community.

The complexities of livestock valuation increase when the disaster causing livestock losses has an impact on market prices. For example, for a highly contagious disease outbreak in a country with extensive exports, market prices can be driven down sharply. This situation reduces the usability of current market data to perform counterfactual analysis on disease price recovery. In such a case, it may be desirable to value livestock losses based on pre-disease prices or price forecasts based on pre-disease market information.

These factors affecting the availability or usability of market data reduces the accuracy of livestock production loss estimates, but it is difficult to quantify the extent of the inaccuracies. Certainly in some markets or for some animal types data are limited to such an extent that livestock loss values would be very difficult to estimate without primary data collection. Such a situation is not the focus of this article. In this study, we focused on quantifying the inaccuracies associated with limited data availability in livestock markets. To do this, we selected a market that currently has robust data. Then, we estimated values using alternative data and methods to mimic the impact of limited data availability. We seek to answer the questions: What if robust data were no longer available? What alternative methods could be used to estimate livestock values? How different are those estimates from the actuals?

Oklahoma bred replacement beef cows can easily be undervalued due to limited market reporting, market thinness, and closed-system farming. This article compared an observed Oklahoma bred beef cow price series to forecasted bred replacement beef cow values estimated with three alternative methods: hedonic pricing, vector error correction modeling (VECM), and cost of production (COP). Each method examined had benefits and drawbacks, especially when forecasting forward to determine future animal values.

BACKGROUND

United States Cattle Production and Marketing

Beef cattle production in the United States is not as highly centralized as poultry and swine production. However, beef cattle production is the highest value livestock industry in the United

[1] Market thinness, in this study, can refer to too few markets, too few cattle being sold in markets, or too infrequent sales in an area.

States, generating $78.2 billion in cash receipts in 2015 when the United States cattle inventory was 89.1 million head (7). Cattle go through multiple stages of production and often change ownership multiple times as a consequence (**Figure 1**).

Beef cattle production begins on grass-raised cow–calf operations. In the 2012 United States Census of Agriculture, there were approximately 913,000 cattle operations in the United States with an average of 99.5 head of cattle and calves (7). Almost 82% of beef cow–calf operations in the United States were small, family owned enterprises with less than 50 head of cows. These small operations held almost 30% of beef cow inventory (7). Less than 10% of cows were held by large operations with more than 1,000 head; however, over 35% of cattle on feed were on large feedlots with more than 1,000 head (7).

Calves primarily sell to feeding operations (feedlots) before slaughter. At weaning, calves may go through a preconditioning or background grazing stage before dry lot feeding or calves may move directly to dry lot feeding. The remaining weaned calves retained for replacement—primarily heifer calves as well as a small portion of bull calves retained for breeding stock—either stay in the herd of birth or sold to other cattle operations. As of January 1, 2016, replacement beef heifers represented 32% of all heifers (7). Replacement cattle are sold via private treaty, production sales—public sales that are held by one or two seedstock producers—or through weekly or monthly public sale yard auctions. Spatial, quality, and time factors all affect United States beef cattle pricing. For example, Blank et al. (8) found that calf and yearling cattle prices were higher in Omaha, Nebraska relative to other parts of the Westerns United States with prices declining with each additional mile of distance from Omaha.

Oklahoma is both a location of extensive cow–calf production as well as an important geographical area for background grazing and cattle feeding for slaughter. Oklahoma collects and reports bred replacement cow and heifer data at seven markets reported through the United States Department of Agriculture Agricultural Marketing Service (USDA-AMS). Sales reports from these seven markets include detailed information on cattle sold as discussed in the data section.

Market and Non-Market Methods

Market data on comparable animals would ideally be used for the valuation of replacement beef cow and heifer losses. Comparable, local transactions data would include characteristics for animal type such as age, weight, and quality. Most commonly, this type of data is available for cattle that are slaughter ready such as cows that have been culled due to reproductive issues and will be slaughtered for beef. These comparable animal transaction data are likely to be region specific and may possibly be privately held by an individual or company, making collection or extrapolation to other regions challenging.

Even when market data are available, forecasting prices forward is potentially necessary when (a) cattle losses in a single time period carry forward into future periods due to production effects (e.g., loss of a calf crop due to abortions will have an impact 2 or more years later) or (b) significant market price impacts may make the use of forecasted prices more appealing than the use of actual prices. Econometric approaches to forecasting allow the data to determine the structure of the model for valuation by taking advantage of long-term cause and effect relationships (9). When prices are known historically and are recorded in a detailed manner non-market valuation methods such as hedonic pricing can be used to estimate cattle values in future periods. Econometric methods, and vector error correction models in particular, assume that the same price dynamics will continue to apply into the future, which may not be true in large-scale disasters. While each of these methods has been used in isolation, none have been applied simultaneously to a replacement cattle data series to assess the implications of limited data availability on forecast accuracy. The methods examined here are summarized in **Table 1**.

Hedonic Pricing

Hedonic modeling is a well-established method for determining the intrinsic, revealed value of factors or characteristics contributing to heterogeneous market prices. Waugh (10) first presented a formalized model to link prices to product quality and characteristics, which was later incorporated into the consumer demand literature (11) and given theoretical foundations

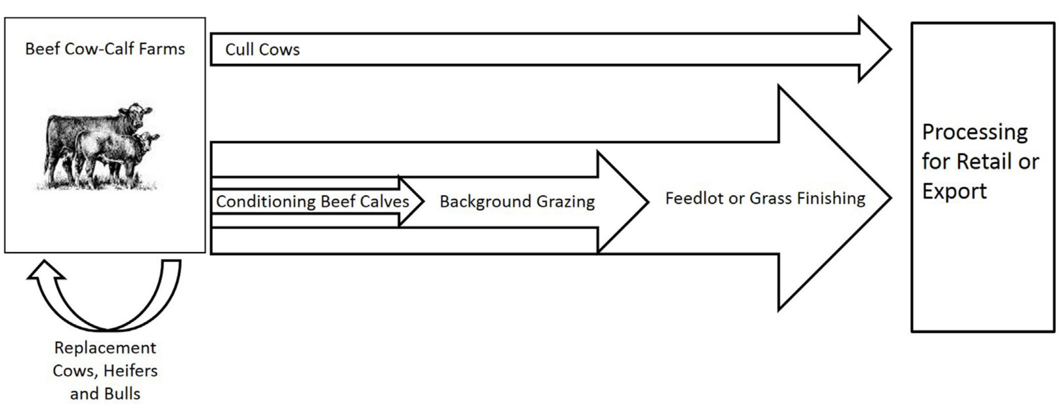

FIGURE 1 | Conceptual flow of beef cattle production in the United States.

TABLE 1 | Alternative methods for estimating the value of livestock lost due to disasters or disease.

Valuation method	Description	Data needs	Benefits	Pitfalls
Observed market values of equivalent animal types	Value losses by using comparable sales at local, publically reporting livestock markets	Recent, local market reports with detail on animal type, age, and weight	Most closely estimates the value of lost livestock that could have been taken to the local market	Markets do not always sell comparable animal types. For extended or extensive natural disasters, market impacts of the event itself may change valuation and in the case of animal disease, will not represent the full losses
Hedonic pricing	Use of sales data to econometrically estimate the value of animal characteristics and attributes	Recent, local market reports with detail on animal type, age, breed, and other unique characteristics of the animal and market	Makes use of market reporting to reveal preferences for animal characteristics	If the animal of interest was not reported, this method cannot accurately predict value. If market data were not available a time intensive and costly survey must be used
Vector error correction model	Use of other livestock price series and input costs to estimate market values for thin or unobserved animal types in the market	Recent market reports on downstream animal products and inputs to production	Makes use of market data readily available and can be extrapolated to areas where data are less readily available	Still requires a price series at some geographic level as the dependent variable and makes the assumption that market structures are similar in the area being extrapolated
Cost of production (COP)	Value losses by calculating the sum costs incurred to raise an animal to a point in time and adds a proportion of proposed future profits back to the animal	Current annual total COP from enterprise budget, accompanying weaned calf price (if using purchased replacement heifer equation)	Data may be specific to a farm, local area or a point in time relative to more extensive time series data	Using basic enterprise budgets results in a single price point. Provides a floor price, not considering price fluctuations for inputs and outputs. Enterprise budgets are not available for all states/regions

(12, 13). Hedonic modeling can use market data or can use values elicited from individuals through a survey. Using recorded prices for differentiated products or services, an estimate of the implicit value that observable and unobservable characteristics contribute to the total price of a good can be determined assuming these characteristics have underlying utility and the value of each characteristic contribute to the total cost of the good or service. In a competitive market, the final market price was determined through the market contract, where the price paid for a good or service was the tangential meeting of a buyers bid function and the sellers offer function. The general form may be written as follows:

$$P_{it} = F(O_{it}, U_{it}) + \varepsilon_{it}, \tag{1}$$

where P are the observed market prices, O are the observable characteristics, U are the unobservable characteristics, and ε was the disturbance term all for good i in time t. These characteristics can be any combination of quantitative and qualitative variables. Using econometric modeling, a formalized function can be estimated.

Hedonic pricing is an established method for valuing cattle based on their characteristics—primarily for feeder or fed cattle, though the literature for those cattle types will not be discussed here. The method has been applied less frequently in breeding cattle. For example, Parcell et al. (14) examined various cow attributes on cow–calf pair pricing in a hedonic modeling framework and found that various factors such as age, breed, size, and gestation status, among others, were significant in explaining pair value variation at auction in 1993. Recent studies that have examined breeding cattle have included an application of hedonic pricing on cow quality characteristics in Oklahoma bred cows by Mitchell and Peel (15) and Colorado breeding bulls by Kessler et al. (16). Mitchell and Peel in particular use the same data series used here to examine the marginal impact of quality and market location on bred cow prices. The authors did find significant, positive impacts on livestock value for younger, heavier, late gestation cows with higher quality.

Kessler et al. (16) looked explicitly at the impact of expected progeny differences (EPDs) and the ability to thrive in the high altitudes of the Colorado Rockies on breeding bull values. The authors found that values were higher for select performance measures such as high yearling weight and EPDs on weaning weight and milk production in progeny as well as a lower pulmonary arterial pressure score that indicated some lessened likelihood the bull would suffer from high altitude disease. Hedonic pricing has been used in other countries for livestock valuation of cattle. For example, Williams et al. (17) examined the impact of cattle characteristics on market values in West Africa and found that young breeding cattle had higher values than market cattle, and among market cattle young zebu steers with excellent body condition received the greatest market premium.

Vector Error Correction Models

If the sort of detailed transaction data used for hedonic pricing is not available, it is possible that more aggregate data may be available. In this instance, a multivariate time series method such as vector autoregressive modeling or VECM that uses economic theory to determine the interrelationships between known input prices and output prices can be used to forecast livestock valuations. Application of this approach for livestock valuation purposes does require that market data be available at a more aggregate level, but the price data do not have to be as detailed as required for hedonic pricing. The goal is to create the most accurate price forecast using the smallest reasonable list of variables that are economically significant (9) for that animal type. For livestock, explanatory variables would be expected to relate to upstream or downstream production, input costs, and consumption as well as longer term exogenous factors.

For example, in the United States, the National Agricultural Statistics Service collects the price received by producers for cows sold in a particular month in dollars per hundredweight. The same survey also collects the value of calves sold, as well as the pasture rental rate in dollars per acre. Lagged heifer calf prices and pasture provide in inputs to cow–calf production, and current calf prices and feeder calf prices serve as the values end products. However, each of these price series could be highly cointegrated and require special handling methodologically.

Multivariate regression analysis allows the interrelationships between commodities to determine value. The vector autoregressive model (VAR) in levels was introduced by Sims (18) and looks at dynamic response of variables to exogenous shocks that are important sources of economic fluctuations (19). Livestock price series often exhibit non-stationary error terms and may follow long-run interrelationships with other livestock price series. When such cointegration is present, first differences are used to achieve stationarity but an error correction term is included in the model that captures the long-run equilibrium position directly. When an error correction term is added to a VAR, the resulting model is a vector error correction model (VECM) as first suggested by Engle and Granger (20). It should be noted that Phillips and Durlauf (21) argued if data are both non-stationary and cointegrated differencing is not necessary, meaning a VAR could be used. Based on the Johansen's cointegrated vector autoregressive model with k lags (22), the data generating process of Y_t that is a n-by-1 vector of price series in time t, can be modeled as a VECM with lags from i to $k-1$:

$$\Delta Y_t = \Pi Y_{t-1} + \sum_{i=1}^{k-1} \Gamma_i \Delta Y_{t-i} + \sum_{l=1}^{J} \theta_l D_l + \varepsilon_t, \tag{2}$$

where ΔY_t was a n-by-1 vector of first-order difference of prices, Y_{t-i} was the vector of lagged own commodity prices, Π was the n-by-n cointegration rank matrix, Γ was a n-by-n matrix of parameters on the lagged price differences, D_l was a matrix of dummy variables to represent seasonal or cyclic trends that has a value of 1 in period l and 0 otherwise, and ε was a n-by-1 vector of error terms in time t (23). Detailed descriptions of VECM models can be found in Kennedy (19) and Lütkepohl (23).

As consolidation in livestock industries increased in the 1980s, analyses of market cointegration became more common. In cattle markets, cointegration has been identified between cash and futures live cattle prices (24), among regional slaughter cattle markets (25), and the impact of mandatory price reporting on regional market cointegration (26). VAR and VECM models have been used to forecast livestock prices for feeder and fed cattle, particularly when simultaneously estimating multiple, cointegrated price series. For example, Fanchon and Wendel (27) looked at the ability of VAR, VECM and Bayesian parameter estimates to forecast feeder cattle prices in Kansas City (400 lb steers and 600 lb steers) and Omaha (1,000 lb steers) as well as the Omaha corn price and a monthly time trend. Forecast quality was tested using mean squared error (MSE), and results indicate that the VAR had the smallest MSE across 4 years but the VECM performed better in the long-run. Although VECM has been applied successfully at the national level, little quantitative information is available on the degree to which national data will over or underestimate a price forecast applied regionally.

COP Method

Application of time-series econometric approaches such as VECM is possible when frequent transaction data are available, but sometimes the available market data are insufficient. In such a situation, another option is to consider producers' costs of production. This non-market valuation method estimates unobserved market values for livestock sold using the total expenses incurred to produce an animal plus a profit margin. Enterprise budgets provide annual estimates of income and expenses for specific production types and species and are usually updated annually for producers to use as an interactive planning tool for the following year. All price variation is captured during these annual updates. Estimates are calculated on an annual basis and represent the average income and expenses for a representative operation for that geographical area (usually state). Expenses are broken into variable and fixed costs, then the sum of these costs was used to proxy a break-even price for a cow. The challenge was determining the net profit margin for breeding livestock, which differs depending of the life stage of the breeding cow. The COP value estimate equation can be written as follows:

$$\text{COP}_{it} = C_{it} + \pi_{it}, \tag{3}$$

where COP was the estimated value for a cow using the COP approach, C was a vector of costs incurred to maintain the cow as she raises a calf i in each time period t, and π is the profit earned for the calf produced i in each time period t plus her cull value at the end of her productive life.

Due to simplifying assumptions using the enterprise budgets there are some limitations of the COP approach when comparing that model to reality based on input and sales transactions in the daily marketplace. Enterprise budgets were calculated on an annual basis such that prices of inputs and outputs were fixed and did not fluctuate throughout the year. In addition, enterprise budgets were built to illustrate a representative operation based on the average costs and returns for producers in the area. Because of the longer production cycle, enterprise budgets for cattle do not capture all costs incurred and income generated in the same year for the same animal. So, there is a delay from when prices are realized at sale and when expenses are incurred to produce the animal being sold at a given point in time. In reality profit margins fluctuate across producers and across time while the COP approach uses the simplifying assumption that the annual average profit earned in a given year was the same earned in previous years.

MATERIALS AND METHODS

The availability or usability of market data affects the accuracy of loss estimates, but it is difficult to say the extent of the inaccuracies. We examined comparable animal transaction data, bred replacement beef cows in Oklahoma and estimated bred replacement beef cow values under alternative methods of hedonic pricing, VECM, COP, and nearest proxy of slaughter cow data. It was recognized that these methods still required larger amounts of data than may be available in some areas; however, each method did have different data intensity and used different types of data. Even where very little data are available, the comparison of these methods provides the parameters for animal valuation that could potentially be collected through primary data collection.

Observed Price Series Data

The actual data used to measure the accuracy of each method evaluated here were a weekly bred replacement beef cow price series from Oklahoma auction markets. The bred replacement beef cow values are for seven traditional auction markets in Oklahoma reported by the Agricultural Marketing Service: Ada report KO_LS757 (28), Apache report KO_LS754 (29), El Reno report KO_LS751 (30), Oklahoma City report KO_LS750 (31), McAlister report KO_LS752 (32), Tulsa report KO_LS760 (33), and Woodward report KO_LS753 (34). The state of Oklahoma was split into East and West regions. East was Ada, Tulsa and McAlister. West was Apache, El Reno, Oklahoma City and Woodward. Each of these auctions sell bred replacement cows one day per week. The weekly transaction data from 2000 to 2015 were collated by the Livestock Market Information Center, and that data series was amended with data for 2016 from AMS report number KO_LS794 (35) which summarizes data from all seven markets.

At these auctions, cows are sold in lots, or groups, of cows that share similar quality or characteristics which were subjectively assigned based on attributes including conformity of size, weight, and visual inspection of cows at the market. This increases the likelihood the seller will receive a higher overall price for the lot of cows as buyers generally prefer to buy a homogeneous group of cows. In these types of auctions where commercial cows are sold, it was rare for cows to be sold individually. Individual sales of cows are more common in private liquidation sales or sales of seedstock cows—cows that will be used to produce other replacement breeding cattle. The factors included in the models included averages for each lot of cows for age, weight, calf weight, and gestation months where applicable. Indicator variables were put in for high quality cows (quality.high), cows that are above average but not quite high quality (quality.highaverage), cows that were below average but not quite low quality (quality.averagelow), and cows that were low quality (quality.low). Cows that were average quality were incorporated in the constant term. HideColor was specifically related to premiums associated with Angus breed-influence cattle in the United States and the popularity of Certified Angus Beef. Black was the predominant hide color due to the popularity of Angus cattle in commercial beef production, so hide color was specified as either "black" or "not-black" by the auction. Other indicator variables for the type of lot–cow only (lot.cow), heifer only (lot.heifer), and cow–calf pairs in the constant—as well as an indicator for Western Oklahoma markets (West) were defined. Indicator variables were also developed for the fixed effects for year, month, and global recession. Since cows are sold in lots, the transaction data describe price ranges (P_{OK}) for lots of cow with similar characteristics (**Table 2**).

The observed data from Oklahoma provide an important resource for valuing beef cattle losses in that state. However, if that data source were not available it is possible to value Oklahoma beef cows based on other data sets. Each year the United States Department of Agriculture's National Agricultural Statistics Service (USDA-NASS) surveys producers on prices received and expenses paid for various types of operations. USDA-NASS data from the same survey are available for cow sales in Oklahoma, but to proxy the effect of only having a national average value the United States average price received was analyzed.

This national data would represent mild data constraints for valuing bred replacement cows in Oklahoma—a situation in which an analyst might believe that reasonably accurate livestock values could still be achieved. Namely, the national USDA-NASS data suffer from a lack of regionally specific data (data accessibility), a high degree of aggregation since bred replacement cows are combined with all other cow sales (market thinness), and a lack of quality characteristics (capital asset value). However, the data should have appropriately captured the underlying market fundamentals that move prices, as illustrated in **Figure 2**. There are regions of the United States that have higher prices for replacement beef cows than others, namely the northern and central plains states. Aggregation across the United States results in data that are expected to undervalue cows from Oklahoma. Further these data were not specific to bred replacement beef cows, but rather averaged across all cows sold in a particular month. Since the majority of cows sold from an operation are older cows that no longer having value as breeding animals, and will consequently be slaughtered, the resulting average price was expected to undervalue bred replacement beef cows. As discussed in section 2.2.2, the VECM estimates value based on upstreamand downstream prices. **Table 3** provides summary statistics on these data.

The USDA-NASS survey data were used to obtain the price cows sold from operations (PUS), for outputs of cow–calf production, and the inputs of cow–calf production. Prices for weaning weight beef heifer calves—500–600 lb feeder heifer calves (Hcalf)—and feeder steers—500–600 lb feeder steer calves (Fsteer)—were used as the downstream product of cow–calf ranching. Franchon and Wendel (36) used a corn feed price for input cost. While this may be appropriate at certain times of the year when supplemental feeding occurs, pasture is the primary feed source for cows in the United States. The inputs of cow–calf production for the purposes of this study were replacement heifers (lagged Hcalf) and pasture rental rates (Rent).

In addition to a time trend, an indicator variable for the fourth quarter of the year (Qtr4) was included. The majority of cows in the United States calve in the spring months. Calves are weaned in the fall, and culling decisions are often made immediately following weaning so that cows are not fed through the winter months. Since the United States cow data include the sale of cull cows, the fourth quarter of the year was controlled for. Exogenous

TABLE 2 | Data description from the Oklahoma bred replacement beef cow data from 2000 to 2016 (20,602 observations).

Name	Notation	Description	Unit	Mean	Range
Dependent variable					
Price	P_{OK}	The price per head for cows in Oklahoma	US dollars per cow	$1,049	$285–$3,800
Explanatory variables					
Region of Oklahoma	West	Binary variable to indicate the West region of Oklahoma	0.1	0.68	0–1
Age range	Age	The cow age for a given set of lots sold in an auction day	Years	5.5	1–12
Weight range	Weight	The cow weight for a given set of lots sold in an auction day	Pounds	1,114	570–1,850
Calf weight range	Calf.Weight	The calf weight for a given set of lots sold in an auction day	Pounds	186	50–1,125
Gestation range	Gestation	The gestation for a given set of lots sold in an auction day	Months	5.4	1–9.5
Quality characterization: high	Quality.High	Binary variable to indicate that the quality of the cows in a given lot was high	0.1	0.21	0–1
Quality characterization: high-average	Quality.HighAverage	Binary variable to indicate that the quality of the cows in a given lot was high-average	0.1	0.07	0–1
Quality characterization: average-low	Quality.AverageLow	Binary variable to indicate that the quality of the cows in a given lot was average-low	0.1	0.01	0–1
Quality characterization: low	Quality.Low	Binary variable to indicate that the quality of the cows in a given lot was low	0.1	0.02	0–1
Hide color	Hide.Color	Binary variable to indicate that cows in the lot had black hide	0.1	0.41	0–1
Lot type: cows	Lot.Cows	Binary variable to indicate that the type of the cows in a given lot are bred or open cows	0.1	0.65	0–1
Lot type: heifers	Lot.Heifers	Binary variable to indicate that the type of the cows in a given lot is heifers	0.1	0.06	0–1
Lot type: pairs	Lot.Pairs	Binary variable to indicate that the type of the cows in a given lot is cow–calf pairs	0.1	0.29	0–1

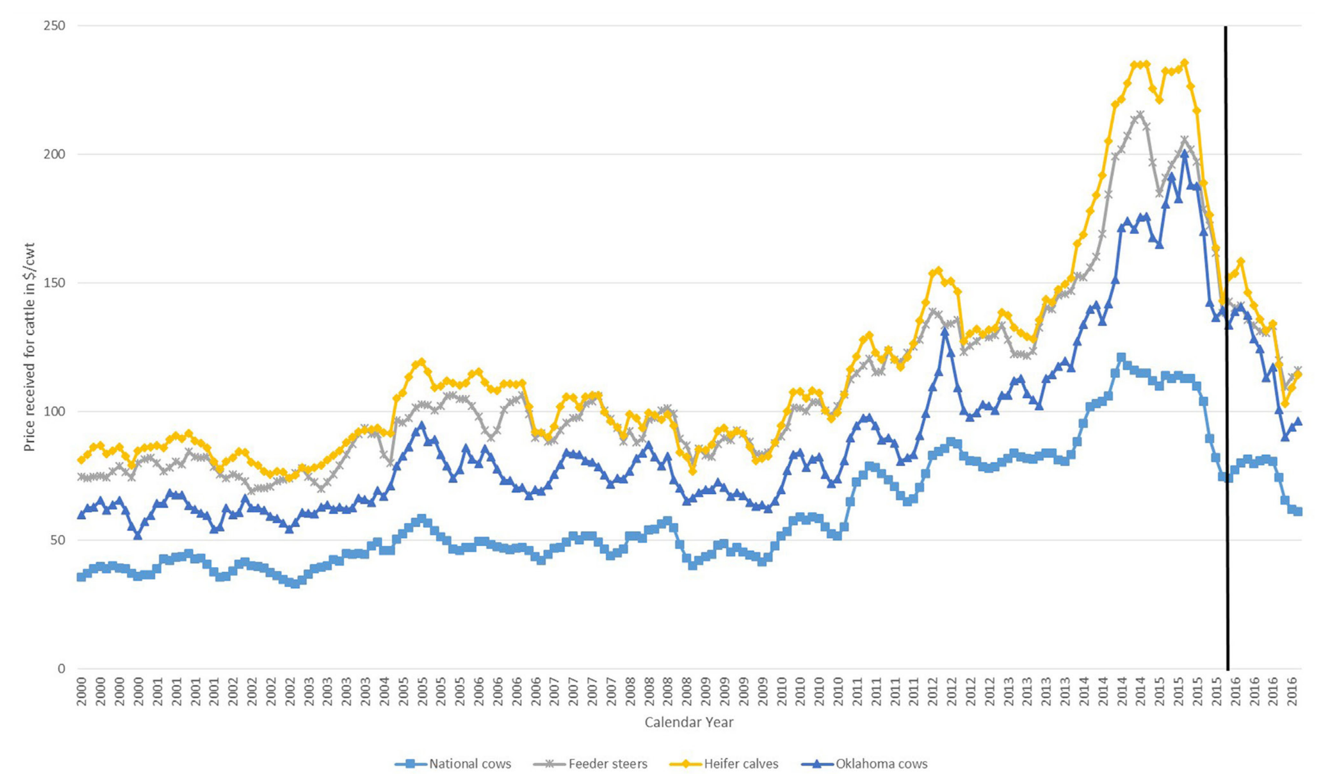

FIGURE 2 | Price received ($/cwt) for cattle by calendar month from 2000 to 2016. Prices received nationally for cows on average in a single month (national cows), national prices received for feeder steers on average in a single month (feeder steer), national prices received for heifer calves on average in a single month (heifer calves), and Oklahoma prices received for bred cows in a single month (Oklahoma cows). The vertical black line indicates the observed prices used for the within-sample forecast comparison. Source: USDA NASS for all except Oklahoma cows. USDA-AMS for Oklahoma cows.

TABLE 3 | Data description from the national average sales price for cattle and national average pasture rental rate from 2000 to 2016 (204 observations).

Name	Notation	Description	Unit	Mean	Range
Cointegrated dependent variables					
National cow price	P_{US}	The monthly price per hundredweight for cows in the United States	US dollars per hundredweight	\$61	\$33–\$121
National heifer calf price	Hcalf	The monthly price per hundredweight for heifer calves in the United States	US dollars per hundredweight	\$117	\$74–\$235
National feeder steer price	Fsteer	The monthly price per hundredweight for feeder steer[a] calves in the United States	US dollars per hundredweight	\$110	\$69–\$215
National pasture rental rate	Rent	The annual price per acre for renting pasture land for grazing	US dollars per acre	\$11	\$8.5–\$14
Explanatory variables					
Fourth quarter	Qtr4	Binary variable that indicates October, November or December	0.1	0.25	0–1
Drought	Dro	Binary variable that indicates years in which pasture conditions were strained due to extraordinary drought	0.1	0.06	0–1
Great recession	GR	Binary variable that indicates the years of the Great Recession (December 2007–June 2009) when financial conditions for leveraging the purchase of cattle were poor	0.1	0.09	0–1

[a]*Feeder steer calves are castrated male cattle that have already been weaned and will enter conditioning, background grazing, and/or dry lot feeding for eventual slaughter.*

TABLE 4 | Specific equations for cattle types.

Cattle type	Cost of production (COP) equation—purchased heifer	COP equation—retained heifer
Weaned calf to 1-year-old	Cost to purchase weaned heifer calf + total cost to maintain calf for 5 months	Total cost to maintain heifer for 12 months + total cost to maintain calf for 5 months
2-year-old Replacement heifer	Weaned calf cost + total cost to maintain heifer for 12 months	Weaned calf cost + total cost to maintain heifer for 12 months
5-year-old Brood cow	2-year-old replacement heifer cost + total cost to maintain cow for 36 months − revenue from 3 calves	2-year-old replacement heifer cost + total cost to maintain cow for 36 months − revenue from 3 calves
10-year-old Cull cow	5-year-old Brood cow cost + total cost to maintain cow for 60 months − revenue from 5 calves	5-year-old Brood cow cost + total cost to maintain cow for 60 months − revenue from 5 calves

factors affecting cow–calf operations were also considered as explanatory variables. Drought (Dro) results in stressed pasture conditions, which can lead producers to reduce the size of their cow herd. This in turn has an impact on the price of cows in the national dataset. Finally, the great recession (GR) that started in December 2007 and is generally considered to have ended in June 2009 had an impact on financial institutions. Many cow–calf producers in the United States depend on borrowing to buy cows. In the wake of the GR, that borrowing may have been more difficult to obtain.

Models

The models will be applied and compared using four profiles of cattle (**Table 4**). These cattle are all black hide, in the West region of Oklahoma (see **Table 2**), and average-low, average or average-high quality.

Hedonic Pricing

In terms of production, knowing the market price and the factors that contribute to the market price can help give an indication of the expected value of an animal with certain characteristics. For this work, factors from recorded market data provide an indication of the expected market value for cattle not traded on the market. The factors included are outlined in **Table 2** of the data section as well as time fixed effects that account for potential temporal effects on market prices. The implicit contribution each variable makes to the price of cattle sold on the cash market was estimated. The empirical model estimated was written as follows:

$$\begin{aligned} P_{OK} = {} & \beta_0 + \beta_1 \text{Age} + \beta_2 \text{Weight} + \beta_3 \text{CalfWeight} + \beta_4 \text{Gestation} \\ & + \beta_5 \text{Quality.High} + \beta_6 \text{Quality.HighAverage} \\ & + \beta_7 \text{Quality.AverageLow} + \beta_8 \text{Quality.Low} + \beta_9 \text{HideColor} \\ & + \beta_{10} \text{Lot.Cow} + \beta_{11} \text{Lot.Heifer} + \beta_{12} \text{West} + \gamma \boldsymbol{T} + \varepsilon, \end{aligned} \tag{4}$$

where P_{OK} were the average observed Oklahoma market prices per cow variables as defined in **Table 2**, T was a matrix of time fixed effects for year, month, and the global recession, β and γ were respective coefficients, and ε was the disturbance term. The base animal included in the constant term was a cow from a paired lot of average quality cows. The use of time fixed effects captured any structural breaks in the data as well as seasonal trends. This model was estimated using pooled ordinary least squares to capture the variation around the full weekly data as opposed to a panel data approach which would have required aggregation or averaging across cow lots per market before estimation due to the multidimensionality of the data.

Vector Error Correction Model

The products of cow–calf ranching are calves for consumption or replacement and cull cows. Prices of inputs and outputs of cow–calf production were included as described in the data section and **Table 3**. Output prices and input prices were included since the production function of outputs—in this case cattle sold—were influenced by the physical inputs and factors of production or in this case by feed prices and the prices of replacement cattle. The data were first tested for structural breaks using the Zivot–Andrews test (37), and a structural break was identified in November 2005. It is likely that this structural break indicates the point when United States markets began to recover from the December 2003 cow identified with typical bovine spongiform encephalopathy and prices for cows in the United States began to improve. The focus of this article was on forecasting into 2016, so the data were truncated at the structural break and the VECM was applied to the remaining 121 monthly data point between November 2005 and December 2015.

Several tests needed to be performed to specify the appropriate number of lags and rank of the VECM—augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests; Akaike information criteria (AIC), Schwarz Bayesian information criteria (SBIC), and Hannan–Quinn information criteria (HQIC) lag tests; and Johansen's maximum likelihood method for cointegration. Greater detail on these tests can be found in Kennedy (19). The ADF and PP unit root tests examined the null hypothesis of a unit root against the alternative of a constant deterministic trend. Results from both tests indicated the presence of unit roots in all of the price data series in levels. However, when the same tests were run on first differences, the null hypothesis was rejected at the 1% confidence level. Thus all of the price series contained unit roots in levels but first-order differences were stationary, and thereby the variables in the series are I(1).

A VAR was specified and examined for 1, 2, 3, and 4 lags in each variable. The AIC, SBIC, and HQIC were used to determine the optimal number of lags by finding the lag that minimizes the AIC, SBIC, and HQIC. The optimal number of lags was 3 under each of the three criteria. Johansen's maximum likelihood method for cointegration was used to determine the optimal rank of the error correction term for the VECM. The rank determines the order of cointegrating vectors included in the VECM. Johansen's cointegration test indicated the presence of cointegration and that a rank of 2 be used in the VECM form specified in Eq. 2.

Cost of Production

Since this comparison was using the Oklahoma price series data, we provided an example of the application of the COP method using an enterprise budget developed by Oklahoma State University (38) for a typical Oklahoma cow–calf ranching operation in 2016. This budget represented the expected income and expenses for an average herd in this area and was updated annually using historical data and specialist recommendations, but could also be modified based on user specific parameters. Variable costs included feed, supplements, veterinary supplies and services, marketing, machinery, labor, and other. Fixed costs included machinery, value of breeding stock, and land. The sum of these categories gave the estimate for the total annual costs at $714.73 per head. For this analysis, we assumed that this cost was held constant across the years explored (i.e., no change in input prices) to understand how values using the COP method change over the duration of a cow's life.

Another assumption was that each cow has a live calf that was weaned and then sold at market (i.e., no death loss). The annual expenses of feeding, getting pregnant and birthing, and keeping the cow healthy were offset by the revenue generated from selling the calves at market each year resulting in profit. For this analysis, we also assumed a fixed price received from weaned calves of $880 (i.e. no change in output price), so the annual profit for years 3 through 10 is $165. Essentially this profit was removed from the value of the cow each year when using the COP valuation method.

Specific equations are presented in **Table 4** for each cattle type. The first year started with valuing a weaned calf. For purchased replacements this was the cost of the weaned calf plus 5 months of costs to maintain that calf assuming they were weaned at 210 days [$714.73*(5/12) = $297.80]. Each following year an additional $714.73 was added in cost and the assumed revenue generated from the sale of her calf, $880, was subtracted for the years she will produce a calf (replacement heifers usually do not produce a calf until their third year). The revenue generated from the calves sold represented the amount the market was willing to pay for that calf, which included the profit margin that was received for raising that calf to weaning. A cow was considered an asset that was producing revenue each year through the sale of calves. This income covered the annual cost of producing the calf, the annual cost of maintaining the cow, and some of the initial investment cost, or capitalization cost, of raising a heifer to maturity as a replacement female in that herd. These values were aggregated to create a cumulative value over time for this cow until she was 10 years old.

RESULTS

Hedonic Pricing Method Results

Select results for the hedonic pricing method are presented in **Table 5**. Time fixed effects were not presented, but can be provided by the authors. Results were presented in absolute terms,

TABLE 5 | Hedonic estimation of replacement beef cow prices in Oklahoma (2002–2015).

Variable[a,b,c]	
Age	−22.93*** (1.04)
Weight	0.58*** (0.02)
Calf.Weight	0.98*** (0.09)
Gestation	2.81* (1.64)
Quality.High	189.91*** (5.94)
Quality.HighAverage	148.64*** (8.95)
Quality.AverageLow	−30.15 (18.99)
Quality.Low	−99.17*** (11.07)
HideColor	37.07*** (4.17)
Lot.Cows	−94.60*** (18.69)
Lot.Heifers	−60.42*** (20.60)
West	8.68*** (4.32)
Constant	−742,537.49*** (154,929.87)
Observations	22,187
R-squared	0.875

[a]*Time effects are not presented, but can be requested from authors.*
[b]*Robust SEs in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.*
[c]*Detailed descriptions of these variables are found in **Table 2**.*

such that the value was interpreted as the dollar change in the average market price of a cow sold in a lot in response to a change in the respective variable. For example, the market price of a cow was estimated to increase by $0.58 per pound.

As expected, results showed there were preferences for age, weight, quality, breed type, and lot type. The extent and direction of these preferences vary by factor, but all significantly affected the market price. Age negatively affected market price by $22.93 per cow as the average age of a cow in a lot increases by a year, implying buyers accounted for future calving potential when purchasing cows. Inversely, average weight and calf weight positively affected market price by $0.58 and $0.98 per pound respectively. This implies a preference for large bodied cows and larger calves. Preference for larger calves was two-fold. First, larger calves typically coincided with larger bodied breeds. Second, weight was proportional to age, wherein larger calves tended to be older and thus a shorter period before the calf represented earning potential through breeding or slaughter.

In line with expectations, gestation months had a positive effect on market price, $2.81 per month of gestation. At most, this was an increase in the price of a cow by $26.70. This perhaps indicated a slight preference for a bred cow, which represented additional earning potential in the form of the calf being carried. This value did not reflect the earning potential of a short-bred cow sold with an unweaned calf at side since most of the reports did not list the cow's stage of gestation.

Binary indicator variables helped identify preference for traits of cows being sold. Determined quality of cows being sold showed a premium for high quality ($189.91) and high-average ($148.64) over average quality. As expected, average-low to low quality had a lower price than cows of average quality. Black hide color also increased the value of a cow in a given lot by $37.07. Location had a positive impact on price. Cows sold in western Oklahoma tended to be $8.68 more than cows sold at auctions in eastern Oklahoma, accounting for all the other variation.

In terms of preferences for the type of lot sold, pairs appeared to be the most preferential. Lots of only cows, bred and open, were expected to decrease the value of a cow by $94.60 than a lot of pairs reflecting the added value of the calf at side. Heifers had a less steep difference of $60.42 per head. This preference may have been driven by potential earnings. Each attribute contributed some intrinsic value to the price of a cow. Using the hedonic pricing method, these values were revealed. For price forecasting, the attributes could be combined and a value could be approximated for various replacement beef cow and heifer types.

Vector Error Correction Model Results

Short-run results from the VECM are presented in **Table 6** for cows and **Table 7** for heifers. The cointegrating equations were less than 1 and significant for the first-order differences of both cows and heifer calves, which was to be expected given the results of Johansson's cointegration test. The short-run effect was based on regression of the first-order difference in the price of cows against lagged prices of explanatory variables as shown in Eq. 2. The AIC, SIC, and HQIC recommended three lags in the model, thus the regression on the first-order differenced dependent

TABLE 6 | Vector Error correction model short-run effects in ΔP_{US}.

Variable[a,b]	Coefficient (SE)	*t*-Statistic
Cointegrating equation 1	0.10 (0.034)	2.96***
Cointegrating equation 2	0.09 (0.05)	1.88*
Constant	0.28 (0.21)	0.13
$P_{US,t-1}$	0.10 (0.13)	0.80
$P_{US,t-2}$	−0.03 (0.10)	−0.24
$Hcalf_{t-1}$	0.076 (0.10)	0.75
$Hcalf_{t-2}$	0.074 (0.10)	0.72
$Fsteer_{t-1}$	0.21 (0.11)	1.85*
$Fsteer_{t-2}$	−0.002 (0.12)	−0.02
$Rent_{t-1}$	−0.33 (1.05)	−0.31
$Rent_{t-2}$	2.25 (1.08)	2.10**
$Qtr4_{t-1}$	−3.86 (0.88)	−4.40***
$Qtr4_{t-2}$	−1.19 (0.77)	−1.55
Dro_{t-1}	0.68 (1.61)	0.42
Dro_{t-2}	2.00 (1.58)	1.26
GR_{t-1}	0.17 (1.63)	0.10
GR_{t-2}	1.31 (1.62)	0.81

[a]"P_{US}" is the monthly price per hundredweight for cows in the United States. "HFeeder" is the monthly price per hundredweight for heifer calves in the United States. "SFeeder" is the monthly price per hundredweight for feeder steer calves in the United States. "Rent" is the annual price per acre for renting pasture land for grazing. "Qtr4" is a binary variable that indicates October, November, or December. "Dro" is a binary variable that indicates years in which pasture conditions were strained due to extraordinary drought. "GR" is a binary variable that indicates the years of the Great Recession (December 2007–June 2009) when financial conditions for leveraging the purchase of cattle were poor. More details are provided in **Table 3.**
[b]The subscript "t − 1" indicates a 1 month lag in prices or a binary variable value from the previous month. The subscript "t − 2" indicates a 2-month lag in price or a binary variable value from 2 months previous.

TABLE 7 | Vector error correction model short-run effects in ΔHCALF.

Variable[a,b]	Coefficient (SE)	*t*-Statistic
Cointegrating equation 1	0.24 (0.09)	2.79***
Cointegrating equation 2	0.24 (0.12)	1.98**
Constant	−0.01 (0.08)	−0.03
$P_{US,t-1}$	−0.34 (0.32)	−1.05
$P_{US,t-2}$	−0.16 (0.26)	0.61
$Hcalf_{t-1}$	0.09 (0.26)	0.33
$Hcalf_{t-2}$	0.14 (0.26)	0.54
$Fsteer_{t-1}$	0.45 (0.28)	1.59
$Fsteer_{t-2}$	0.02 (0.29)	0.08
$Rent_{t-1}$	−1.53 (2.65)	−0.58
$Rent_{t-2}$	2.76 (2.72)	1.01
$Qtr4_{t-1}$	−6.06 (2.22)	−2.73***
$Qtr4_{t-2}$	−3.91 (1.94)	−2.02**
Dro_{t-1}	−1.52 (4.08)	−0.37
Dro_{t-2}	2.05 (4.01)	0.51
GR_{t-1}	−4.69 (4.11)	−1.14
GR_{t-2}	4.98 (4.10)	1.21

[a]"P_{US}" is the monthly price per hundredweight for cows in the United States. "HFeeder" is the monthly price per hundredweight for heifer calves in the United States. "SFeeder" is the monthly price per hundredweight for feeder steer calves in the United States. "Rent" is the annual price per acre for renting pasture land for grazing. "Qtr4" is a binary variable that indicates October, November, or December. "Dro" is a binary variable that indicates years in which pasture conditions were strained due to extraordinary drought. "GR" is a binary variable that indicates the years of the Great Recession (December 2007–June 2009) when financial conditions for leveraging the purchase of cattle were poor. More details are provided in **Table 3**.
[b]The subscript "t − 1" indicates a 1 month lag in prices or a binary variable value from the previous month. The subscript "t − 2" indicates a 2-month lag in price or a binary variable value from 2 months previous.

variable will include 2 (or $k - 1$) lags. The explanatory variables explained 64% of the variation for cows in the short-run as measured by the R^2. Cow price responded to feeder steer price, pasture rental rate, and the fourth quarter indicator. As feeder steer price increased, cow price declined a month later. This may have indicated the slight lag in the seasonal market cycles of cows as compared with feeder cattle. As pasture rental rate per acre increased, cow price increased two months later. This was a reasonable relationship since increased rental rates could have served as an indicator of higher demand for calves. In the fourth quarter of the year, cow prices declined. It was expected that more cows are sold in the fourth quarter after the majority of calves are weaned in the fall, resulting in a decline in prices.

Explanatory variables did a poorer job explaining variability in heifer calf prices with an R^2 of 40%. This may be the result of input and output variables being customized to cow–calf production. It was also likely that other variables, such as the price of beef, were affecting heifer calf prices. The only variable that significantly explained the variation in the first-order differenced heifer calf price was the indicator for the fourth quarter. The majority of calves are weaned in the fall, gaining weight—and value—throughout the following winter, spring and summer.

The coefficients of the cointegrating equations in **Tables 6** and **7** indicated that the short-run relationships did adjust back to the long-run equilibrium. The speed of that adjustment was indicated by the coefficients in **Table 8**. In absolute values, smaller adjustment coefficients indicated a faster movement back to a stable long-run equilibrium. Expectations based on output prices, such as feeder steer prices, were adjusted to more quickly than exogenous shocks, such as drought. The fourth quarter, drought, and rent adjustment coefficients indicated a slower move back to equilibrium. Only the adjustment coefficient for the GR was insignificant in the long-run.

To forecast, results on the short-run coefficients were forecast forward based on the monthly cow and calf price series in the short-run but accounted for long-run adjustment to feeder steer price, rent, the presence of drought and the fourth quarter to attain long-run stability.

COP Approach Results

The COP approach estimated an annual value for these animals and results are presented in **Table 9**. This approach revealed the break-even point when enough calves have been sold to pay for the costs that have been incurred to raise a female to sexual maturity, through gestation, and up to weaning her first calf. This was important since no income was received for a female up weaning her first calf.

The cost for purchased heifers was always higher than retained heifers; however, the market only records the price for heifers sold from operations. Prices for replacement heifers sold at market incorporates the split of future earning potential between the buyer and the seller, allowing the seller to realize some profit from heifer sales. However, purchase of heifers incurs cost as well. Since the value of retained heifers was based on the cost incurred to produce that heifer, it makes sense that the COP approach would value purchased heifers higher than retained heifers reflecting the additional cost of purchase. If the portion of earning potential was accounted for as well, the $166 difference between purchased and retained 2-year-old replacement heifers would not occur in theory.

TABLE 8 | Vector error correction model long-run effects.

Variable	Coefficient (SE)	*z*-Statistic	Coefficient (SE)	*z*-Statistic
Constant	64.07		−24.36	
P_{US}	1		0	
Hcalf	8.9 e−16		1	
Fsteer	−0.46 (0.11)	−4.33***	−1.30 (0.08)	−15.49***
Rent	−8.75 (3.74)	−2.34**	5.84 (2.99)	1.96*
Qtr4	92.92 (7.34)	12.66***	−52.10 (5.86)	−8.88***
Dro	−15.74 (6.13)	−2.57***	6.07 (4.90)	1.24
GR	−2.31 (5.62)	−0.41	4.32 (4.49)	0.96
Chi-squared	338.6918***		896.79***	

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

TABLE 9 | Annual cost-of-production results for 2016.

Cattle type	Purchased heifer	Retained heifer
Weaned calf to 1-year-old	$1,178 (184%)	$1,013 (158%)
2-year-old Replacement heifer	$1,893 (187%)	$1,727 (170%)
5-year-old Brood cow	$1,397 (120%)	$1,231 (106%)
10-year-old Brood cow	$570 (62%)	$405 (44%)

The market prices for cull animals were driven by beef demand and supply. The 10-year-old brood cow represents a fully depreciated cow in the COP method and may not reflect her remaining earning potential. This COP approach only took into account the maintenance cost, breeding cost, and the realized profit from selling her calves each year. Since the use of that cow changes from reproduction to supplying protein, this category would be the most difficult for the COP approach to estimate.

Within-Sample Testing Results

Using the methods above within-sample comparison examined the accuracy of the three methods in determining animal values. This was achieved by forecasting monthly prices throughout 2016 and comparing the forecasted prices to the corresponding observed monthly market data. The year 2016 was chosen since it was the most recent complete year of data as of the time of this study. From a market perspective, 2016 was a year characterized by high beef and cattle market prices earlier in the year that declined throughout the year and recovered slightly in December. Typically, a cattle market cycle lasts 4–6 years, and 2016 fell mainly on the downside of that cycle. Pasture conditions were generally good in 2016, so no dramatic change in cow prices from stress-marketing was observed.

To achieve the best comparison possible, the Oklahoma observed market prices were transformed into a price per hundredweight ($/cwt) for cows sold and applied to eight representative females:

- 550 lb open replacement commercial heifer under 1 year of age of average quality
- 550 lb open replacement Angus heifer under 1 year of age of high quality

- 1,050 lb 2-year-old bred commercial replacement heifer of average quality
- 1,050 lb 2-year-old bred Angus replacement heifer of high quality
- 1,250 lb 5-year-old bred commercial brood cow of average quality
- 1,250 lb 5-year-old bred Angus brood cow of high quality
- 1,200 lb 10-year-old bred commercial brood cow of average quality
- 1,200 lb 10-year-old bred Angus brood cow of high quality

Actual values were calculated for each month in 2016 for these eight representative females by taking the price in $/cwt in that month and multiplying it by the weight of that female in cwt. These actuals were compared with the monthly price forecasts for the same eight described females using each method. Each method captures beef cattle characteristics differently. The hedonic pricing method is the only method that will allow for a price differential between the high quality Angus females and the average quality commercial females. The hedonic pricing and VECM methods allow variation across months, but the COP method gives an expected value across the entire year. These differences help capture the tradeoffs of estimating livestock values when different levels of data are available.

Figure 3 shows the forecasted values (vertical bars) versus actual values (horizontal lines) for each month of 2016 for average quality commercial beef females. The MAPE for each comparison is in **Figure 4** where the shaded box represents a 10% error above and below 0. **Figures 5** and **6** show the forecasted versus actual prices for high quality Angus replacement females and the MAPE of each monthly comparison respectively.

For the heifers, most methods overvalued the representative heifers selected as compared with observed prices. The VECM performed well for the weaned heifer calves and replacement heifers, resulting in the lowest MAPE in 90% of the months for weaned heifers and 75% of the months for replacement heifers. The hedonic pricing method forecasted values that overestimated average quality females, more so for open heifer calves. Weaned calves were reported in the lot type pairs in the Oklahoma data. This diluted the reporting on the actual price of a weaned calf. Though the hedonic pricing method was the closest value for the high quality heifers, most of the time the methods overestimated or underestimated the high quality open heifers by more than 10%. This indicated that no one method may be best suited to valuing high quality heifers in a specialized market.

For 5-year-old brood cows, the MAPEs were overall lower as compared with younger or older beef females. This likely reflected how common it was in the data to have 5-year-old cows being sold for replacement. The COP method performed well when compared with the more data intensive econometric methods. This could be because the enterprise budget was reflective of the costs specific to Oklahoma. So, where the VECM in particular suffered from using data that were too aggregated, the COP offset that effect slightly. The COP method, where retained heifers and purchased heifers were combined, had the lowest MAPE in 75% of months for the 5-year-old average quality brood cow; hedonic pricing resulted in the lowest MAPE in the other 25% of the months. The lack of seasonal adjustments appeared to contribute to the error associated with COP, and particularly the effect of timing on breeding and retention decisions before winter when feeding was most intense. However, the hedonic pricing method tended to do much better when forecasting higher quality replacement cows as measured by the MAPE. The VECM results were often close to the results of the hedonic pricing model for bred, high quality replacement females.

The VECM chronically undervalued the 5-year-old replacement cows even after accounting for the influence of cull cows on the national price series. This likely reflected the averaging in the data series used, both across cow types (cull versus replacement) and across regions. The VECM forecast undervaluation was only exacerbated when examining high quality cows. The VECM did a better job of valuing cows later in the year as prices declined. This may reflect the relative strength of this estimation method in capturing price dynamics.

In the valuation of the 10-year-old brood cow that has a few productive years remaining, the COP method struggled to accurately forecast. Across methods, for a 10-year-old average quality brood cow the MAPE was under 10% in 8 of 12 months, and the VECM resulted in a MAPE under 10% in 5 of those 8 months. It may be easy to value a 10-year-old cow as a cull intuitively, but there may be times in the market, particularly during periods of herd expansion, when cows were retained longer or when other beef cattle producers were looking for "bargains" to get a few more calves on the ground. When the 10-year old brood cow was an Angus cow of higher quality, the ability to predict value was decreased. Across methods, the MAPE was under 10% in only 4 of 12 months. The VECM was often the closest estimate of the 10-year-old brood cows that were high quality, but always on the low side as compared with the actuals. For the hedonic pricing method, data may have played a role in the inaccuracy of results. There were fewer older brood cows sold on the market in Oklahoma compared with other types so the impact of individual characteristics may be heavily influenced by younger cows. Also, the hedonic pricing method did a poorer job of forecasting the mid-year market lows and overall declining trend through the latter part of the year. Instead the forecasted price remained fairly consistent through the 12 months varying by no more than $250.

There were months in which no observed data were available to compare to. These were months were it was less common to sell certain types of animals. As mentioned previously, most calving occurs in the spring and weaning occurs in the fall. So it was less likely that an observed market price for a weaned heifer was seen in the summer. An unexpected benefit of these results was the ability to see the ranges that prices might have fallen in during those months where no market data were observed for comparison.

DISCUSSION

An enhanced understanding of livestock valuation improves estimates of impacts due to production shocks and is an understandable metric of loss for decision makers in both the public and private sectors. The range of value differences across

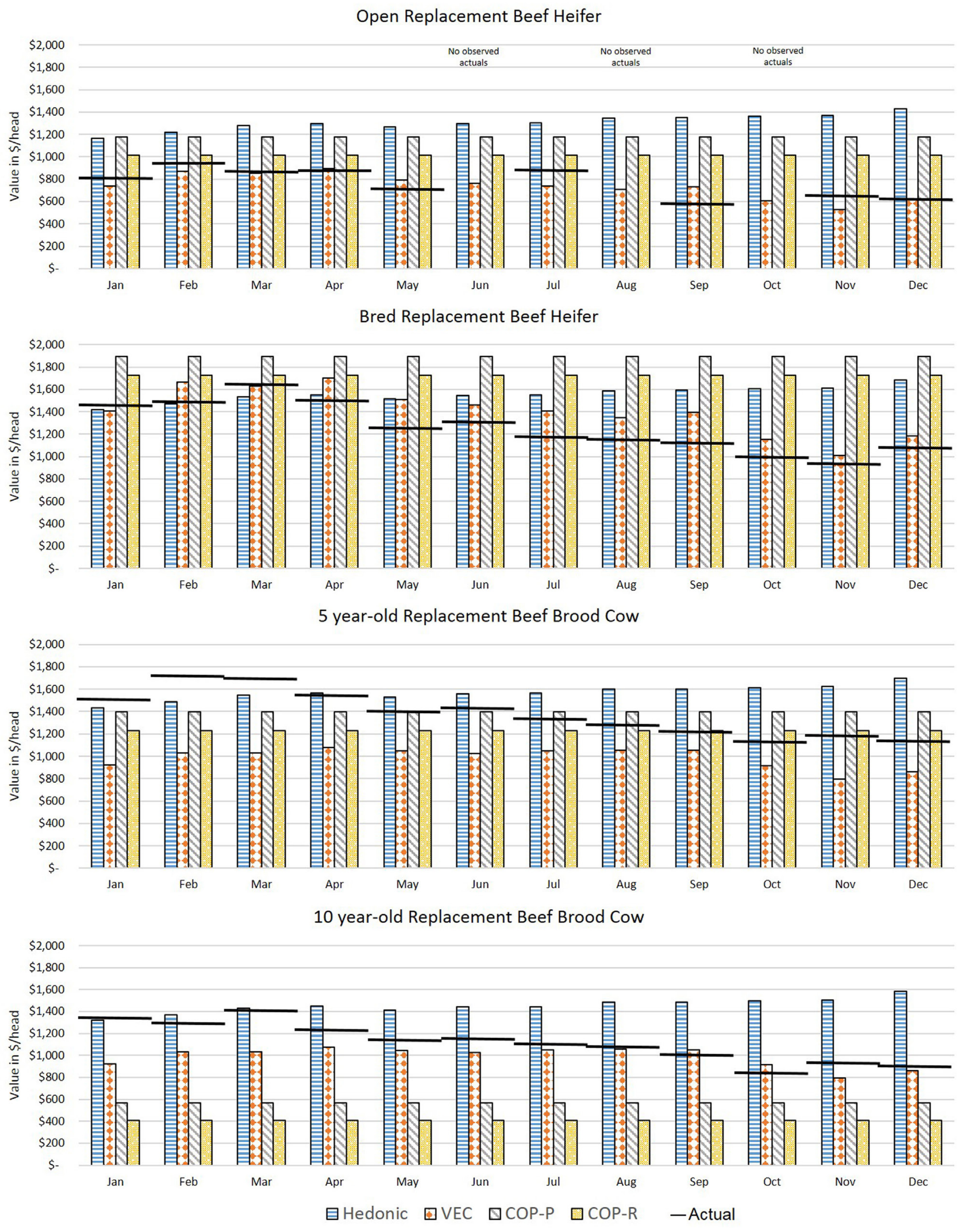

FIGURE 3 | Comparison of forecasted and actual values from January to December 2016 for average quality replacement beef females. Forecasted values (vertical bars) versus actual values (horizontal lines) for each month of 2016 for average quality commercial beef females. Source: analytical results.

regions, time and animal types needs to be understood before determining whether comparable market data are appropriate for livestock valuation. Livestock valuation methods are often data intensive, requiring complete market data for a similar type of animal or region, extensive cost data, or survey implementation. The accuracy of livestock values estimation is inhibited by data limitations. The methods explored in this article may provide avenues to estimate value in a way that is accessible and consistent with economic theory. It is up to the individual researcher to determine the level of regional aggregation, time frame and tolerance for inaccuracy that is most appropriate for the question being asked.

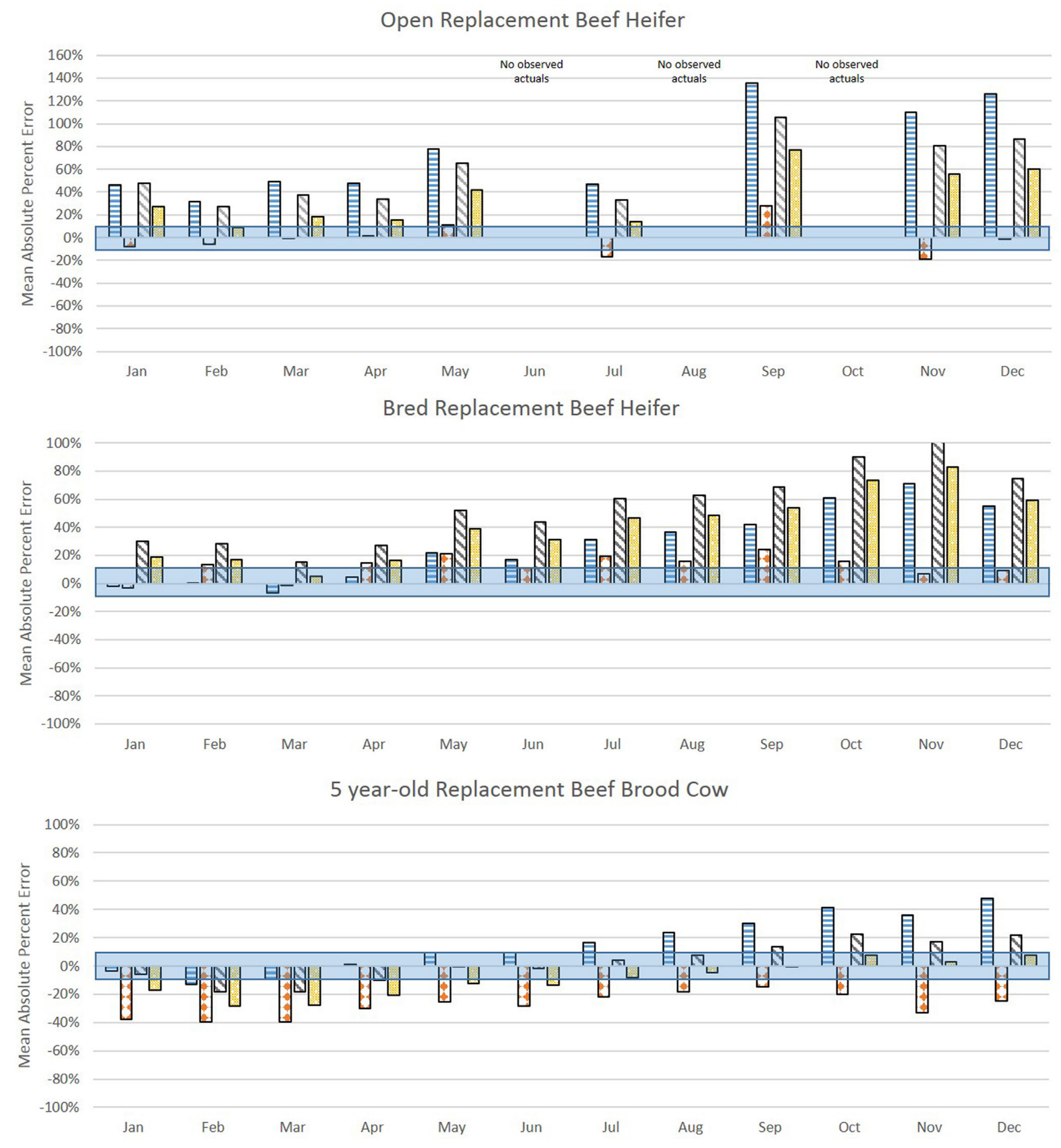

FIGURE 4 | Continued

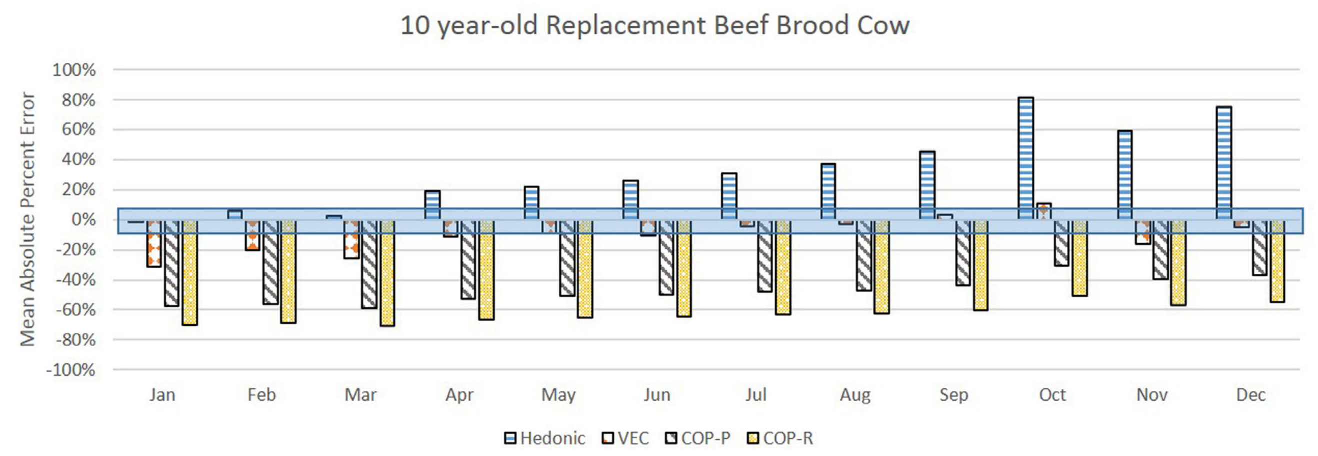

FIGURE 4 | Mean absolute percent error (MAPE) of forecasted values compared with actual values from January to December 2016 for average quality replacement beef females. The shaded bar represents 10% above and 10% below a MAPE of 0%. Source: analytical results.

This article applied three alternative methods to the valuation of bred replacement beef cows in Oklahoma and utilized data that were a proxy to varying types of market data limitations. The data used for the hedonic pricing method were limited by region, but rich in detailed animal characteristics. The vector error correction model data were limited in detail, but representative of a larger geographic space and accounted for upstream and downstream price impacts across time. The COP approach is limited in time variation but may be more accurate for a specific operation and does not require extensive time series data. Generally the direction and magnitude of the coefficients associated with factors impacting beef cow prices in the hedonic pricing method and vector error correction method align with what was seen in previous literature. Price forecasts for eight replacement beef cow or heifer types were created from each method, and compared in each month of 2016 to observed prices in Oklahoma. Results suggested that data intensive econometric approaches such as the hedonic pricing method or vector error correction model did approach the real values; however, where the hedonic pricing method overvalued replacement females (63% of MAPES were positive for average quality females and 60% of MAPES were positive for high quality females), the VECM method undervalued females (65% of MAPES were negative for average quality females and 84% of MAPES were negative for high quality females). The least data intensive method using COP data performed reasonably well for young and middle-aged cows, though the lack of seasonality impacted accuracy. It may be possible to refine these COP estimates by using seasonal indices to capture common market patterns on feed input costs and cattle prices received.

Within-sample forecasting results suggested that all three methods more frequently overvalued monthly values for heifers in 2016 and all three methods did a poorer job of valuing 10-year-old brood cows that may have some remaining productive life. Examining each method individually across all eight beef female types, for average quality beef females the VECM forecast resulted in a MAPE under 10% for 33% of forecasted months, followed by hedonic pricing at 24% of the forecasted months and COP at 14% of the forecasted months. For high quality females, the hedonic pricing method worked best producing a MAPE under 10% in 36% of the forecasted months followed by the COP method at 21% of months and the VECM at 14% of the forecasted months.

There is a tradeoff between data intensity and forecast accuracy, and some general conclusions were made from this analysis. First, given that certain methods performed better than others in this application, researchers tasked with livestock valuation may need to utilize different valuation methods—or even multiple valuation methods—depending on the type of livestock affected and the types of market transactions data available. Second, the context of the data mattered for the accuracy of the forecasts. Consider the VECM results which ranged from a MAPE of less than 1% up to a MAPE of 60% when compared with observed Oklahoma bred replacement beef cow prices. However, performing the same within-sample forecast comparison against the observed values of the aggregated national cow prices the VECM was based on, the MAPE was less than 1% on average and never exceeded 10% error in any given month. Thus, the majority of the error was in the application of the results to the Oklahoma bred cow dataset, and particularly the high quality bred cow data set. Third, in several months the MAPES were quite large and well above what would be considered a reasonable tolerance for error. This indicated that even in a situation where market data were available that would appear to be sufficient for quantitative analysis, researchers should be aware of the potential impacts of data constraints. It is possible that data could have been cut further for the hedonic pricing method and a different model could be estimated for each of the eight cow types. The aggregation in the national data used for the VECM would not allow for that approach to break down types down further to test for increased estimate accuracy.

Focusing this analysis in Oklahoma had benefits. It was possible to quantitatively measure forecast inaccuracy because a bred

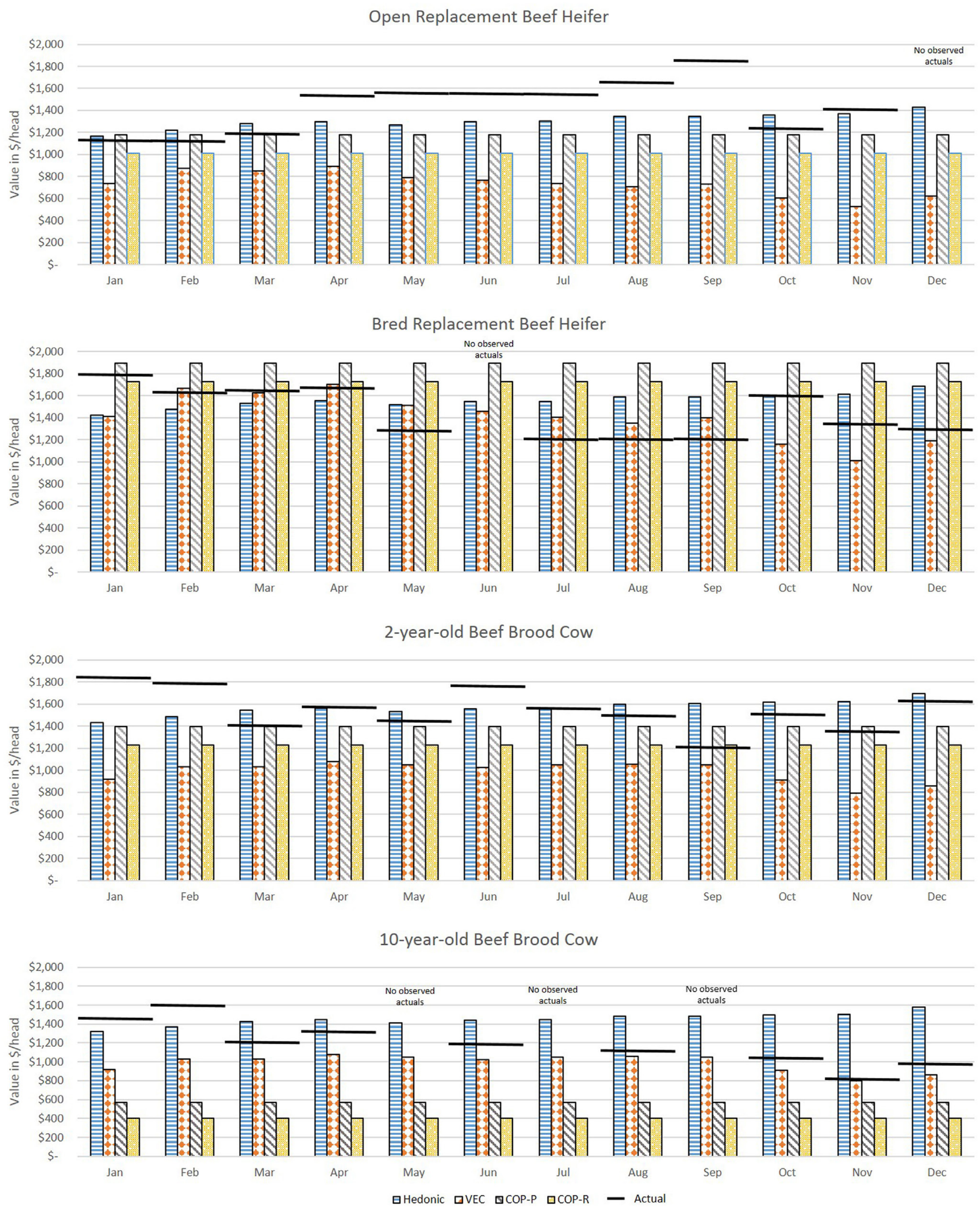

FIGURE 5 | Comparison of forecasted and actual values from January to December 2016 for high quality Angus replacement females. Forecasted values (vertical bars) versus actual values (horizontal lines) for each month of 2016 for high quality Angus beef females. Source: analytical results.

FIGURE 6 | Mean absolute percent error (MAPE) of forecasted values compared with actual values from January to December 2016 for high quality Angus replacement females. The shaded bar represents 10% above and 10% below a MAPE of 0%. Source: analytical results.

replacement beef cow data set was available, and Oklahoma has regional importance for cattle production. However, there are few other regions of the United States that have these same data availability and it is difficult to say whether conclusions could be extended to other geographic regions. Further analysis would be needed to determine the extent to which these conclusions hold in different phases of the marketing cycle—for example, when beef cow herd inventories are expanding resulting in an upward trend in prices.

Other methods such as stated preference or contingent valuation could be examined to determine whether forecast accuracy is improved. For example, stated preference elicitation may be useful, particularly if characteristics affecting the value for an animal were less tangible, such as livestock serving as a status symbol, providing draft power, or livestock production as a hobby. Another, more complex approach of price differential modeling could be used to estimate the cattle prices in the United States as well. Applications of price differential modeling suggested that the approach provided a useful supplement to market data in the short-run, but does not provide complete data to cattle owners for decision making in the long-run. In addition, there are other approaches to estimate the profit applied back to each cow by manipulating known market data. Such applications were beyond the scope of this study. Alternative methods to valuing losses that use different types and intensities of data are available and can be employed within a degree of error when doing livestock valuation. It is hoped this study encourages continued innovation of ways to utilize constrained market data for livestock valuation, because market data are likely to be an increasingly scarce resource into the future.

AUTHOR CONTRIBUTIONS

AH was the project leader, estimated the VECM, and lead manuscript development. JT estimated the hedonic pricing model and contributed to manuscript development. CH and KJ estimated the cost-of-production method and contributed to manuscript development. All the authors met the contribution requirements for authorship per the author guidelines.

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Conflict of Interest Statement: 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.

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frontiers in Veterinary Science

ORIGINAL RESEARCH
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Farmer and Veterinarian Attitudes towards the Bovine Tuberculosis Eradication Programme in Spain: What Is Going on in the Field?

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The effectiveness of health interventions against bovine tuberculosis (bTB) is influenced by several "*non-biological*" factors that may hamper bTB detection and control. Although the engagement of stakeholders is a key factor for the eradication programme's success, social factors have been often ignored in the control programmes of animal diseases, especially in developed countries. In this study, we used a qualitative approach to investigate perceptions, opinions, attitudes, and beliefs of farmers, and veterinarians who may influence the effectiveness of the Spanish bTB eradication programme. The study was carried out in two phases. First, 13 key representatives of different groups involved in the programme were interviewed through exploratory interviews to identify most relevant themes circulating in the population. Interviews focused on strong and weak points of the programme; reasons for failure to achieve eradication; benefits of being disease free; future perspectives, and proposed changes to the programme. Based on these results, a thematic guide was developed and detailed information was gained through face-to-face in-depth interviews conducted on a purposive sample of 39 farmers and veterinarians. Data were analysed following an ethnographic methodology. Main results suggested that the bTB programme is perceived as a law enforcement duty without an adequate motivation of some stakeholders and a general feeling of distrust arose. The complexity of bTB epidemiology combined with gaps in knowledge and weak communication throughout stakeholders contributed to causing disbeliefs, which in turn generated different kinds of guesses and interpretations. Low reliability in the routine skin test for bTB screening was expressed and the level of confidence on test results interpretation was linked with skills and experience of public and private veterinarians in the field. Lack of training for farmers and pressure faced by veterinarians during field activities also emerged. Few benefits of being bTB free were perceived and comparative grievances referred to wildlife and other domestic reservoirs, sector-specific legislation for bullfighting farms, and the absence of specific health legislation for game hunting farms were reported.

Understanding reasons for demotivation and scepticism may help institutions to ensure stakeholders' collaboration and increase the acceptability of control measures leading to an earlier achievement of eradication.

Keywords: bovine tuberculosis, qualitative epidemiology, ethnography, sociological factors, disease eradication

INTRODUCTION

The influence of social factors on public health interventions is well known in human medicine and several studies taking these aspects into account have been done (1–3); however, these aspects have been often ignored in the implementation of animal health programmes. Recently, the situation has changed and the interest on the influence of social factors in the control programmes of animal diseases has greatly increased. As a matter of fact, several studies have highlighted the importance of understanding the attitudes and behaviours of the different stakeholders involved, as their actions have a great influence on the effectiveness and sustainability of such programmes (4–9).

The use of participatory approaches to investigate attitudes and behaviours is a valuable tool to conduct such studies (5). The fundamental principle of participatory research is that emphasises "*knowledge for action*" and a "*bottom up approach*" in contrast to conventional research, which is more "*top-down*" (10). The use of such approaches provides a voice to the different stakeholders increasing, in that way, the understanding of health problems and the options for their prevention, control, and surveillance (11).

In the last years, different qualitative methods, such as semi-structured interviews, focus group discussions, ranking and scoring methods, or visualisation and diagramming, have been used in the field of Veterinary Medicine (5). The increased interest in these approaches has been reflected in an increase in participatory epidemiology activities in animal health, especially from 2012; however, most of them have been implemented in Asia and Africa but not so much in Europe (12).

The engagement of stakeholders and the level of acceptability of the interventions are key factors for the success of control programmes and surveillance systems (13). The application of qualitative methods can ensure the access to specific type of information and local knowledge otherwise impossible to collect; it can contribute to identifying information gaps, understanding local cultures and beliefs, and setting priorities (11, 14). Moreover, it allows investigating risk perception amongst stakeholders and the impact it may have on their response and commitment towards health policies. Finally, since the application of qualitative methods results in a high level of community participation throughout the decision process of designing health interventions, it ensures a more accurate implementation and helps in developing good relationships with communities and in reducing later conflicts.

Bovine tuberculosis (bTB) in Europe represents a significant obstacle to the sustainability of the livestock sector and since 1964 many efforts have been made to eradicate it (15). Even though, substantial improvement in the prevalence reduction has been achieved, the eradication of bTB remains a challenge. While in some countries, such as Germany, The Netherlands, and Belgium, the eradication campaigns have been successful; in other countries, such as the United Kingdom, Ireland, Italy, and Spain, the disease is still endemic. Furthermore, recently the re-emergency of the disease in officially bTB free countries has been reported (16).

In Spain, several aspects of bTB epidemiology have been investigated. In particular, research has been conducted on: spatial and spatiotemporal dynamics of the disease (17–19); risk factors associated with bTB persistence and new infections in cattle herds (20–22); the role of wildlife reservoirs (23–31) and the role of other domestic reservoirs (32, 33).

In spite of all these studies, no major decrease in the bTB herd prevalence has been observed in Spain over the last decade (1.8% in 2004 and 1.7% in 2014) and, in 2015, the bTB prevalence has increased to 2.8% (34). This context makes it necessary to study other factors that might influence the success of the national bTB eradication programme, such as sociological and anthropological factors that have never been central in such investigations.

In this study, we aim to investigate farmers and veterinarians' perceptions, opinions, attitudes, and beliefs about the Spanish bTB eradication programme by using a qualitative approach in order to assess the influence that these aspects may have on the effectiveness of the programme.

MATERIALS AND METHODS

Study Areas

The study was carried out in two Autonomous Communities of Spain, Andalusia and Catalonia, as representatives of high- and low-prevalence areas, respectively (**Figure 1**).

In Spain, Regional Veterinary Services (RVS) has been set up in each Autonomous Community under the coordination of the Spanish Ministry of Agriculture and Fisheries, Food and Environment. Moreover, each administrative county has a Local Veterinary Service (LVS) attached to the RVS. Besides, there are accredited veterinarians working in the field (private sector) that collaborate in carrying out disease prevention programmes. Often, they are also responsible for hygiene, productivity, and treatment programmes of the same farms.

Catalonia

Catalonia is located on the north-eastern extremity of the Iberian Peninsula; it consists of 4 provinces and 42 counties. The Autonomous Community can count on 47 official veterinarians working on bTB at the LVS and 113 specialised private veterinarians supporting the routine screening tests for bTB in about 1,900 beef herds, 700 dairy herds, and a few bullfighting herds. Since 2008, the bTB herd prevalence at regional level remained lower than 1%, decreasing to 0.04% in 2013, but in 2015 bTB herd prevalence slightly increased to 0.32% (34).

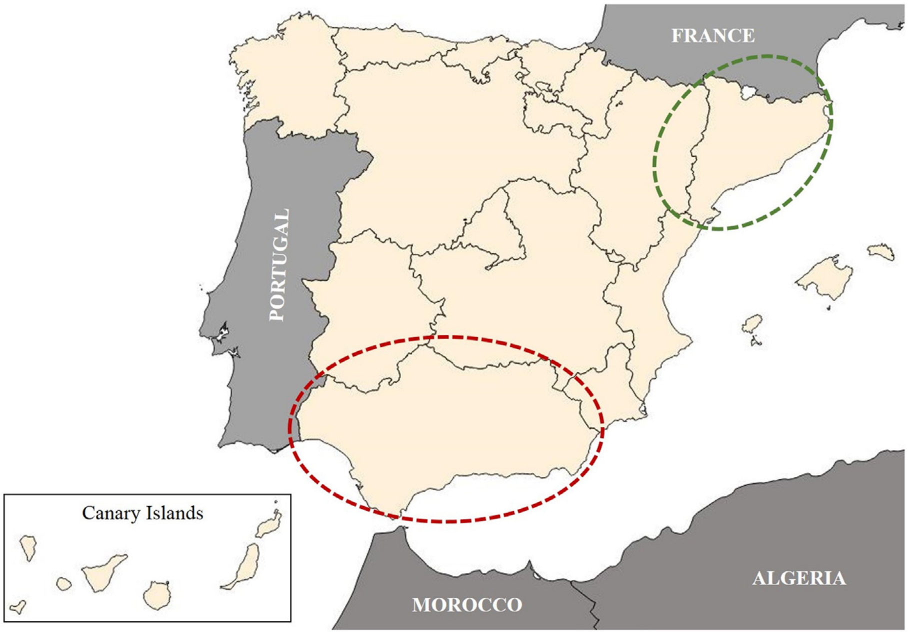

FIGURE 1 | Map of Spain by Autonomous Communities is shown in the figure. Dotted ellipses indicate the two study areas. Red dotted ellipses: Andalusia, high prevalence area. Green dotted ellipses: Catalonia, low prevalence area. The Canary Islands, an Autonomous Community of Spain located in the Atlantic Ocean (west of Morocco), are illustrated in box at the bottom-left corner of the map.

Andalusia

Andalusia is located in southern Spain and it is divided into 8 provinces and 62 counties. There are 63 official veterinarians, operating at the LVS, directly engaged with the bTB eradication programme. These are assisted by about 270 specialised private veterinarians for the implementation of routine screening in about 5,300 beef farms, 800 dairy farms, and 400 bullfighting farms. Over last 10 years, herd prevalence for bTB in this region has persisted above 4% and in the last 2 years has dramatically increased to 11% in 2014 and 17% in 2015 (34).

Study Design

The present study was carried out in two phases, first, exploratory interviews followed by qualitative in-depth interviews, and it was conducted by a team of veterinarians, sociologists, and anthropologists. In both phases, people to be interviewed were selected through a purposive sampling.

In accordance with the national and institutional guidelines, ethical approval was not required for this study as it did not include samples or experiments on people but only their expression of opinions in relation to a specific topic.

With regard to the informed consent of participants: as the interviews were anonymous, the data were analysed anonymously and the decision to participate in the study was solely up to each contacted person, we did not consider it necessary to obtain a written consent. We orally informed all participants of the elements of consent and permission was obtained verbally before starting the interview.

At the beginning of each interview: interviewers introduced themselves and the contacted person was informed on the study design and its objectives.

It was explained that the participation was voluntary and completely anonymous (data collection and analysis) and that they could stop the interview at any time.

It was explained that there were no expected risks and no expected personal benefits associated with participation in the study. We also asked their approval for using information collected through the interview and for using direct quotes from them and these would only be cited as from a "farmer" or "veterinarian," keeping the anonymity.

Exploratory Interviews

The aim of these interviews was to identify major themes to be considered and further investigated in the qualitative in-depth interviews. For that purpose, we used a *stakeholder sampling* strategy (35) by which we selected a particular segment of the population having concrete experience with the issue at stake (bTB) or being strongly affected by it. The concrete population segments were "farmers" and "veterinarians" of the study areas.

Overall, 13 key representatives were interviewed. In the high-prevalence area (Andalusia), three veterinarians of the public sector (one from the RVS, one from the LVS, and one from the diagnostic laboratory), two private veterinarians (operating in two different counties), and three farmers, covering the main livestock production types: beef, dairy, and bullfighting farms were interviewed. In the low-prevalence area (Catalonia), two veterinarians of the public sector (RVS and LVS), one private veterinarian, and two farmers (beef and dairy farmers) were also interviewed.

The interviews were conducted face-to-face following a general script in order to allow, as much as possible, open and informal conversations in which key aspects on the bTB management could emerge.

Each interview lasted between 50 and 120 min and focused on the following six points: (i) strong points of the bTB eradication program; (ii) weak points of the bTB eradication program; (iii) reasons for the failure of bTB eradication; (iv) future perspectives; (v) proposed changes to the bTB eradication program; and (vi) benefits of being bTB free.

Two of the researchers, taking handwritten notes, were present at each interview. After the interview, notes from both researchers were compared in order to transcribe the main arguments expressed. The review of the transcription of the different exploratory interviews was done in different steps. In a first step, the transcription of the exploratory interviews was send to all the team members (paper's authors) and then we organised a group meeting where all team members discussed together the results from those interviews. After that, the team of sociologist prepared a first draft of the interview guide for the qualitative in-depth interviews and they send it to all the authors of this paper for the final discussion and agreement.

Interviews in Andalusia were conducted at the beginning of December 2014 (from 1/12 to 11/12), whereas in Catalonia they were performed in two rounds: middle July 2015 (from 17/07 to 22/07) and middle September 2015 (from 15/09 to 21/09).

Qualitative In-Depth Interviews

This study phase was aimed at gaining detailed information on the themes that emerged from the exploratory interviews in order to understand perceptions of farmers and veterinarians and their interpretation of problems related to the eradication of the disease in Spain.

A "thematic guide" was developed based on previous results and it provided an orienting framework of the different stakeholder groups.

Overall, 14 veterinarians and 25 farmers were interviewed (**Table 1**), applying a *maximum variation sampling* strategy in order to identify as many different "speeches" as possible (36). By this way, we aim to sample for heterogeneity in order to understand how bTB was perceived by people holding different social positions in the field. With this strategy in mind, we selected a small number of samples maximising the diversity relevant to the research question. Diversity was achieved by segmenting the sample (both of farmers and veterinarians) through two key criteria guaranteeing very different daily experiences: territorial criteria (high/low-prevalence areas) and type of farming (beef, dairy, and bullfighting farmers). By doing so, we obtained a wide spectrum of daily experiences and points of view, enough to "saturate the discursive space" related to the subject, which is what was intended by our qualitative sampling procedure.

TABLE 1 | Structure of the sample for the qualitative in-depth interviews.

	Low-prevalence area (Catalonia)	High-prevalence area (Andalusia)	*N*
Farmers (*N* = 25)	Six beef farmers	Eight beef farmers	14
	Four dairy farmers	Three dairy farmers	7
	One bullfighting farmer	Three bullfighting farmers	4
Veterinarians (*N* = 14)	Three veterinarians of the public sector (official veterinarians)	Four veterinarians of the public sector (official veterinarians)	7
	Three private veterinarians	Four private veterinarians	7
Total	17	22	39

Semi-structured face-to-face interviews, lasting between 90 and 150 min, were used for this study phase in order to provide in-depth understanding of the participant's perspective and, at the same time, to allow all opinions and viewpoints to be brought up during interviews. Only one interviewer was present for each interview (an anthropologist in Andalusia and two different sociologists in Catalonia). Interviews were tape-recorded and transcribed by the team of sociologist and anthropologists.

Prior to the interview, a formal letter (headed by the university logo and signed by the research team) was hand delivered to each interviewee and permission was secured at all levels. Participants were informed about: (a) the purpose of the study; (b) the research team members and their university department (with the address, telephone, and email of the main researcher); (c) the freedom to accept or not to do the interview and to withdraw from it at any time; and (d) the explicit guarantee of anonymity and confidentiality of their personal opinions. Interviews only took place after they were read, and verbal consent was obtained from each participant.

In order to make respondents as comfortable as possible during the interview and encourage them to talk extensively and "freely ramble on," all in-depth interviews started with a few general questions, which respondents could answer easily. These questions were related to their professional career, type of livestock farm, daily working activities (i.e., activities performed in current job position, in the field, in the farms, etc.), and variation in their workday across the year. As the interview progressed, the interviewer gradually introduced new elements in the conversation directing it to more specific and targeted topics.

Interviews in Andalusia were conducted and transcribed between March and October 2015, whereas in Catalonia they were conducted and transcribed between January and June 2016.

To ensure the protection of sensitive data, recordings and transcripts were stored by the research team, and access to them is reserved exclusively for members linked to this research, who have undertaken to maintain the confidentiality and anonymity specified in the mentioned letter. All the real names of individuals and companies, entities, or institutions were eliminated in order to ensure anonymity. Instead, an alphanumeric code that identifies each sample was assigned to each interviewed person. Each interviewee was warned that if any of the phrases pronounced during the interview were used to illustrate results in some public document, and that in no case would the person's name be mentioned, but replaced by the mentioned code or attributed to the sample as a whole.

An ethnographic methodology was used in this study. Interview transcriptions were analysed through a method inspired on the grounded theory approach, based on the constant comparisons between data of the whole dataset (of all transcripts) and on the use of a repeated coding, which provided a scheme of the main perceptions, opinions and beliefs circulating in the discourses of the study population (37). The records of the interviews were examined thematically by noting and coding each piece of information in the transcriptions. The coding allowed highlighting all central emerging themes. In relation to the internal reliability, the interviews' transcriptions were compared and discussed between three different members of the research team. Each researcher did it separately, and they met to agree on the relevance of the emerging themes and its interpretation. A single meeting was enough to agree on a common interpretation because there were no major discrepancies.

For each theme that emerged, the most representative sentences were transcribed in their original language (i.e., Spanish or Catalan) and included in the Supplementary Material. From here onwards in the text, we will refer to each sentence as {S*n*}, where "S" means "sentence" and the "*n*" is an integer number whose value represents the unique identifier of the sentence.

RESULTS

Exploratory Interviews

Following the general script previously described, the exploratory interviews allowed us to identify the following themes to be further investigated in the second study phase.

Strong Points of the bTB Eradication Program

In general, the programme was perceived as technically correct. The increased implication of veterinary services, the systematic use of the interferon-γ assay (IFN-γ), and the implementation of mandatory training courses for veterinarians (public and private) organised by the Spanish Ministry of Agriculture and Fisheries, Food and Environment were perceived as major improvements of the programme in the last years (**Figure 2**).

Weak Points of the bTB Eradication Program

Main weak points were related to the communication flow, organisational issues and the suitability of the human and economic resources currently assigned to the programme (**Figure 3**).

Concerns were expressed in relation to the coordination with the labs, the experience of official veterinarians who supervise private veterinarians in performing the single intradermal test (SIT), the lack of homogeneity in the implementation criteria of the bTB eradication programme and the lack of human resources. Interviewees also mentioned that some of the implemented control measures were too restrictive or infeasible.

Some stakeholders reported the comparative grievance that is generated due to the special legislation that is in place for bullfighting herds, as in herds with cattle that is older than 24 months bTB testing is not performed. Moreover, the presence of wildlife and other domestic bTB reservoirs not included in the eradication programme was perceived as a comparative grievance by farmers and contributed to generate uncertainty on the achievement of bTB eradication.

Reasons for the Failure of bTB Eradication

Arguments that emerged in this section were related to the lack of confidence in the results of the diagnostic tests, the heterogeneity in the bTB detection capacity among the different slaughterhouses, the relationships among stakeholders and pressures faced by private veterinarians when interpreting the skin test (**Figure 4**).

The importance of the level of implication of the different actors in the bTB eradication programme (i.e., farmers, private, and official veterinarians) and the lack of trust between farmers and official veterinarians were also mentioned.

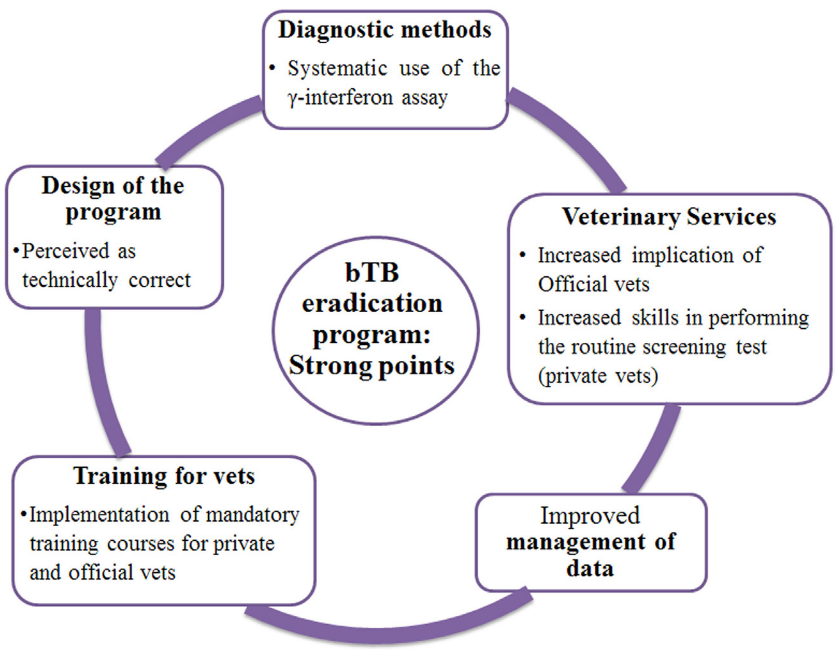

FIGURE 2 | Schematic representations of the main themes emerged from exploratory interviews as "Strong points of the bTB eradication program"; results for Andalusia and Catalonia are presented together. "vets" = veterinarians.

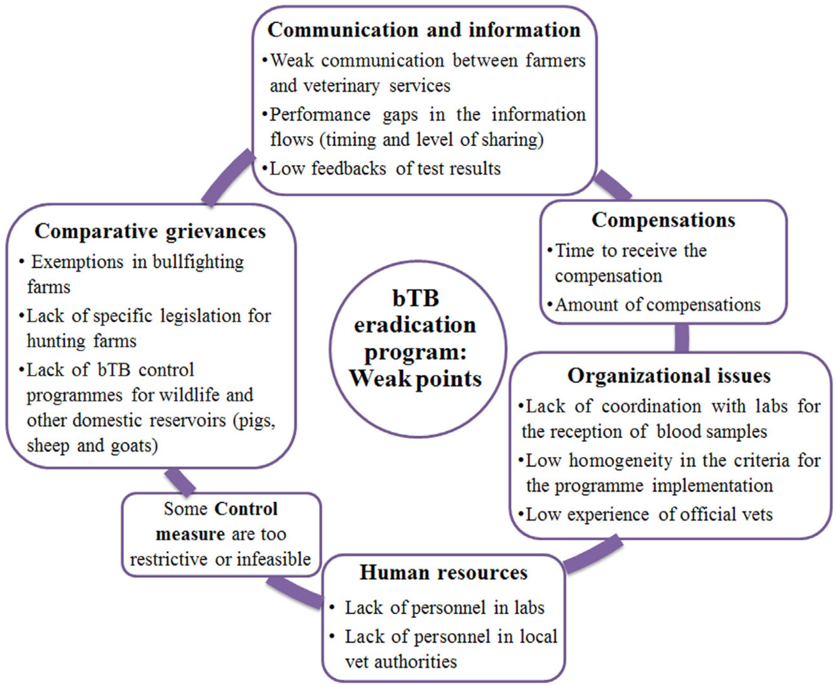

FIGURE 3 | Schematic representations of the main themes emerged from exploratory interviews as "Weak points of the bTB eradication program"; results for Andalusia and Catalonia are presented together. "vets" = veterinarians; "labs" = diagnostic laboratories.

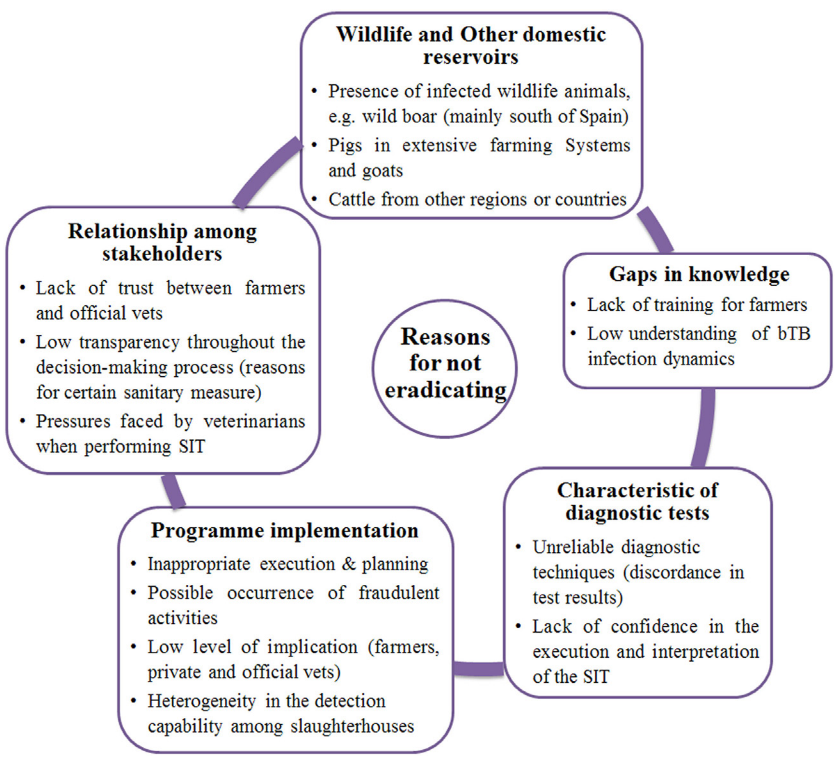

FIGURE 4 | Schematic representations of the main themes emerged from exploratory interviews as "Reasons for the failure of bTB eradication"; results for Andalusia and Catalonia are presented together. "vets" = veterinarians; "SIT" = Single Intradermal Test.

Moreover, the reason for certain sanitary measures was somewhat unclear or not well understood and the presence of infected wildlife animals was perceived as a major obstacle for the bTB eradication, especially in the south of Spain.

Future Perspectives

In this section, very different views were expressed (**Figure 5**): some people considered that it was at all possible to eradicate the disease and others considered that it will only be possible to maintain a low prevalence.

Proposed Changes to the bTB Eradication Program

The different stakeholders considered that improvements to the bTB programme should focus on training (especially for farmers) and communication. It was also mentioned that measures related to movement restrictions should be relaxed (**Figure 5**).

Benefits of Being Free of bTB

With the exception of some awareness on the potential zoonotic risk of bTB reported from some people, few benefits of being bTB free were perceived (**Figure 5**). The perceived economic impact of the disease was mainly related to the consequences of animal movement restrictions and, therefore, benefits of being bTB free were mainly related to the reduction of control activities at herd level (i.e., frequencies of routine screening) and the removal of restrictive measures on animal trade.

Based on these results, we developed a thematic guide to be used in the qualitative in-depth interviews (**Table 2**) which outlined the most relevant themes identified and itemised as follows:

(i) bTB detection and control (reliability of diagnostic techniques, organisation and human resources, measures provided for by the programme).
(ii) Training, information, and communication (training for farmers and veterinarians, level of implication of different actors, and communication and information flows within and between levels and categories).
(iii) Role of wildlife and other domestic reservoirs (wildlife reservoir and other domestic species, game hunting areas and farms, specific legislation for bullfighting farms).
(iv) Perception of social aspects (i.e., reciprocal relationships among stakeholders).
(v) Risk perception on bTB and benefits of eradication (risk perception of economic aspects, such as costs of implementing the programme or direct and indirect losses due to the disease).
(vi) Future perspective on the progress of bTB and proposed changes to the programme.

In-Depth Qualitative Interviews

Main results obtained from the ethnographic reports of both areas are described below. Since we did not observe major differences in attitude and opinions between the two study areas,

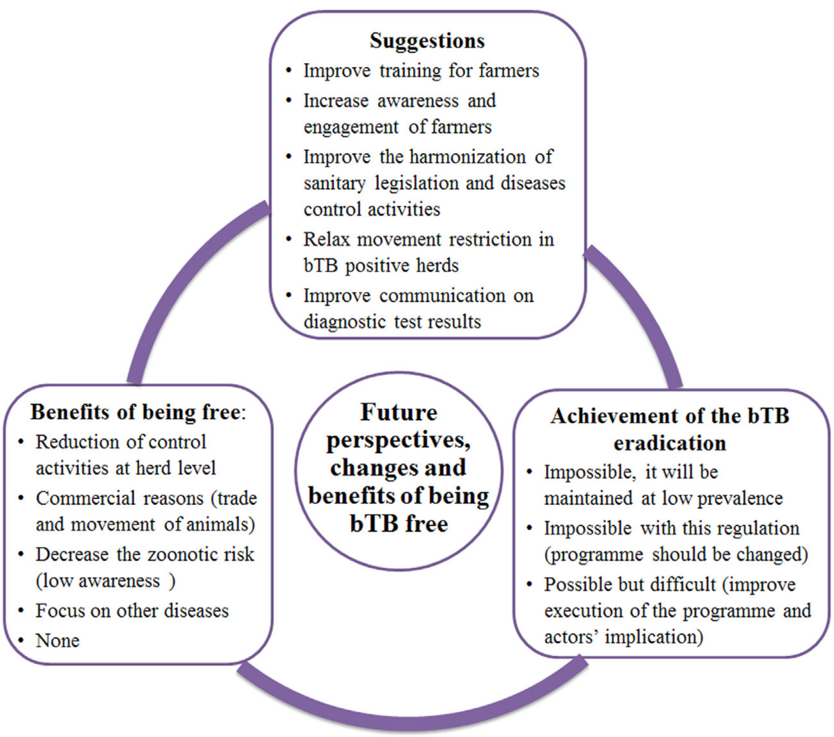

FIGURE 5 | Schematic representations of the main themes emerged from exploratory interviews as "Future perspectives," "Proposed changes to the bovine tuberculosis (bTB) eradication program," and "Benefits of being bTB free"; results for Andalusia and Catalonia are presented together.

TABLE 2 | Thematic guide (topics and example questions) used in the qualitative semi-structured in-depth interviews aimed at gaining detailed information on perceptions and opinions of farmers and veterinarians about the bovine tuberculosis (bTB) eradication programme in Spain.

❖ *Establishing the first contact: Short opening questions*
- ➢ What is your professional career path?
- ➢ What are your main daily work activities? (i.e., activities performed in current job position, in the field, in the farms, etc.)
- ➢ What is your typical workday like? How does it change throughout the year?
- ➢ What is your experience with the eradication programme? (if not already mentioned)

❖ *Topic 1: Evaluation of the bTB eradication program and control measures (adequate, insufficient, excessive, or illogical)*
- ➢ Are frequencies of routine bTB screening adequate?
- ➢ Ask about diagnostic test: reliability of single intradermal test (SIT) and the interferon-γ assay (IFN-γ), differential diagnosis and diagnostic interference with PTB.
- ➢ Coordination with labs and availability of diagnostic kits for the interferon-γ assay (IFN-γ).
- ➢ SIT execution: are good practice applied? (i.e., cutimeter use, measure fold, etc.)
- ➢ What do you think about the official controls on the execution of the SIT? (adequate, insufficient, excessive…). Should they be addressed appropriately? How?
- ➢ What do you think about the sector-specific legislation for bullfighting herds? (bTB screening exemption for cattle older than 24 months, legal argument that justifies this measure).
- ➢ Do you think that the applied control measures are adequate? Too strict? Are they feasible and applicable? (existence of fraudulent activities, reasons for fraudulent activities to occur, effects of administrative pressures on fraud, and motivation)

❖ *Topic 2: Other reservoirs*
- ➢ What do you think about the role played by wildlife species in the maintenance of the disease? Is it a real problem or just an excuse? Is the administration doing enough to control and solve this matter?
- ➢ What do you think about hunting areas and activities, hunting farms and the mixed hunting-farming subsistence strategy?
- ➢ What do you think about the role of other domestic species? (sheep, goats and pigs in extensive systems, others…)

❖ *Topic 3: Perception on social aspects, management, and organisational dynamics*
- ➢ Relationship with other social factors and institutions (dependence, confidence, mistrust, and mutual perception):
  - Official and private veterinarians.
  - Private Vetrinarian group (ADGS).
  - Slaughterhouses (evaluation of activities).
  - Farmers and farmers' association.
  - Veterinary medicine companies.
  - Administration (evaluation of communication and administration operations).
- ➢ What you think about the organisation and the mode of operation of the ADGS?
- ➢ Inter- and intra-institutional coordination (between different Ministries or between central and local level of the same institution).
- ➢ Implication and transparency of administration (particularly in respect to the diagnostic test results).
- ➢ Information and training for farmers and veterinarians (level of dissemination, evaluation of courses and events on bTB, etc.).
- ➢ What kind of information, format, and method would be the most effective and appropriate to train the different groups about the risk of bTB and its control?

❖ *Topic 4: Risk perception on bTB and its economic impact*
- ➢ Do you think bTB can produce direct and indirect losses on production?
- ➢ Do you think bTB can represent a risk for human health?
- ➢ Are the human resources destined to the implementation of the bTB eradication programme adequate? (impact on testing frequencies and test execution)
- ➢ What do you think about the administrative sanctions and their application? Are they adequate?
- ➢ What do you think about the farm subsidies? Are they adequate? May they influence farmers' decision process regarding management of animals and farm's infrastructures? How?
- ➢ What do you think about financial compensation paid to farmers for the slaughter of bTB test-positive cattle? (adequacy of compensation, agility of procedures, etc.)
- ➢ Influence of the farming type and farms' characteristics to the correct implementation of the programme (i.e., difficulties due to the extensive farming system, adequate state of, reluctance among bullfighting farmers to test animals for difficulties in management).

❖ *Topic 5: Proposed changes to the programme*
- ➢ What would you change of the bTB eradication programme?
- ➢ Would you improve some control measures already in place?

❖ *Topic 6: Future perspective on the progress of bTB*
- ➢ What are main benefits to be bTB free?
- ➢ What do you think on the failure of bTB eradication campaign?
- ➢ Is the failure of bTB eradication mainly due to the persistence or to a continuous spread of the disease?
- ➢ Can the eradication be achieved? How? When?

results are presented together, highlighting differences when these were identified.

bTB Detection and Control

A generalised lack of confidence in the bTB diagnostic tests clearly emerged during the in-depth interviews. Both farmers and veterinarians expressed strong uncertainties on the reliability of test results, although this perception was widespread especially among farmers; so much that some people used the term "lottery" when explaining their perception about test results {S1}. Actually, farmers expressed that they do not want to have any bTB-infected animal in their herd, but that they want to be sure that the test-positive animal is truly infected {S2}.

Uncertainties were mostly associated with the SIT and mainly attributed to the lack of confirmation of positive results and they asked for the application of complementary tests for the verification of the final results {S3}. Reasons provided were the absence of visible lesions in slaughtered animals {S4}, discordance of results between the SIT and the IFN-γ {S5} and the use, as screening test, of the SIT instead of the single intradermal comparative cervical test (SICCT), as it could give cross-reactions with paratuberculosis or other environmental mycobacteria {S6}.

Concerns with the existence of false-negative results were also mentioned but mainly by the official veterinarians and related to bad practices in the field and erroneous execution of the SIT. This group, more than others, disagreed on the systematic use of the SICCT and defended the use of SIT as the screening test. Even though, they admitted a certain degree of subjectivity in the interpretation of the SIT results and a great influence of the level of experience of the veterinarian in question {S7} emphasising and warning about the importance of the professional training of veterinarians {S8}.

Private veterinarians also highlighted that a correct application of the SIT is not always easy as some cattle are difficult to manage and farms do not always have the necessary infrastructure. The importance of having good infrastructure was highlighted by several interviewed, not only to correctly perform the SIT but also to prevent veterinarians from risk of injuries and lesions. The lack of support from the official veterinary services to ensure the existence of adequate infrastructures for bTB testing {S8b} was also mentioned.

On the other hand, the IFN-γ was generally perceived as a better diagnostic test than the SIT; thus, its introduction and systematic use was perceived as positive by most of the participants in the study {S9}. Especially, veterinarians highlighted that the IFN-γ is a valid and helpful tool to dispel doubts on diagnostic results {S10} and that it reduces pressure on veterinarians during field activities as it is performed in labs {S11}. However, some concerns were expressed on the IFN-γ regarding the possible existence of false-positive animals {S12} and the high cost of this diagnostic test that makes its systematic use not always feasible {S13, S14}. Furthermore, the difficulties in sending blood samples to the laboratory on time from remote areas and the lack of support from the labs {S15} were also reported. Finally, another issue mainly expressed by private veterinarians and farmers was the over-saturation of some laboratories and the consecutive delay in receiving the results due to the lack of coordination {S16}; on their side, official veterinarians acknowledged that organisational problems have happened in some occasions due to the lack of enough personnel in the lab. Lack of enough human resources for bTB activities was also related to a deficient post-mortem inspection in the slaughterhouses or field activities supervision {S17, S18}.

Another important issue that emerged in relation to the perception of the diagnostic techniques as unreliable was the lack of understanding of test results (e.g., doubtful results in animals around 1 year of age). Both farmers and private veterinarians mentioned experiences with doubtful results that nobody has been able to explain and clarify {S19, S20}, and they asked for further investigation and more efficient dissemination of information {S21}.

In the last few years, official veterinarians were in charge of supervising the performance of the skin test done by the private veterinarians. This has generated some conflicts as some private veterinarians consider that the official veterinarians who have to supervise them do not always have sufficient experience {S22}. Furthermore, the eradication programme in areas of high prevalence (as is the case of the south of Spain) has established a stricter lecture of the SIT in infected farms by which doubtful results are considered as positive. This measure has not been well accepted by the interviewed farmers and private veterinarians who would wish to verify positive results {S23}, whereas official veterinarians do think that it is a good change that will benefit the eradication programme.

The screening intervals set by the bTB eradication programme for routine testing were considered functional and adequate by official veterinarians and most of private veterinarians and farmers, albeit they asked for more coordination among different sanitary controls to avoid generating stress in animals and workers {S24}.

Only in certain rural areas of Andalusia, the implementation of two screening round per year was perceived as excessive, especially by farmers, due to the difficult management of beef cattle in extensive farming systems. In addition, farmers expressed the management difficulties that they face during the bTB testing, especially in those farms with extensive managements or in bullfighting farms {S25}. Direct loses due to abortions, work hours, injured animals, and decrease in milk production were mentioned as a major issue related with bTB testing, especially in those infected herds subjected to a high frequency of tests.

Some criticisms were reported in Andalusia with regard to the sector-specific legislation for bullfighting cattle farms (bTB screening exemption for cattle older than 24 months), although different points of views were expressed {S26–S28}. Some interviewees considered that no exceptions should be allowed with bullfighting animals, while others justified this measure and evaluated it as reasonable on the basis of their difficult management, the risk of injuries in animals of high value or changes in their behaviour making them unfit for bullfighting {S29}. However, even within the group of farmers that agree with the exemption of bTB testing, not everyone agreed with the argument of difficult management as still these animals are subjected to other health measures (such as vaccination or deworming). The high genealogical value of bullfighting animals and the economic difficulties that the sector is going through were considered as more relevant for these persons.

In relation to the control measures provided by the programme, the huge economic consequences derived from movement restrictions was mentioned, especially for those farms without infrastructures for fattening animals. This measure was perceived as too restrictive and as the origin of fraudulent activities. Nevertheless, in the last few years, farmers have been allowed to send these animals to specific fattening units; a measure that has been positively received, despite that calves are sold at a lower price {S30}.

Training, Information, and Communication

An improvement in the application of the bTB programme in the last few years was highlighted and mainly attributed to the organisation of mandatory training courses. Both official and private veterinarians acknowledged that some bad practices in the field were largely caused by a lack of knowledge and training among veterinarians {S31}.

Official and private veterinarians also expressed the importance of organising such activities also for farmers, ensuring that they could have access to all the available information by increasing awareness and knowledge on the diseases as well as on its impact to the farm {S32, S33}. Some of the interviewees also emphasised the importance of training for farmers in order to improve the understanding of sanitary measures provided for the bTB eradication programme and increase its acceptability {S34}.

Among farmers, the lack of understanding of test results and control measures gave rise to some disbelief and to different guesses, for example, that a high mutability rate of the Mycobacterium invalidates the diagnostic tests and that bTB is just an excuse to reduce the cattle population in Southern Countries {S35}.

It was not clear which should be a more efficient way to deliver such training as some people expressed concerns due to the high number of courses that are already organised for farmers {S36} and a lack of motivation in relation to animal health by some of them {S37}. Among the different stakeholders, private veterinarians were identified as one of the more adequate professionals to inform farmers and raise their awareness on the disease, as they are the ones that usually inform farmers on other matters {S38}.

In relation to the effectiveness of communication between stakeholders, different opinions were reported. On the one hand, some farmers expressed the lack of meeting places to exchange information and to express doubts and concerns on the disease and its control. As a matter of fact, most times they have learnt about the bTB eradication programme and changes in the regulation by talking to other farmers in the bars {S39, S40}.

On the other hand, some other farmers expressed that the communication through their private Vetrinarian group (ADGS) was good enough and they were informed of any changes through them {S41}. Most of the farmers also reported that they would prefer attending informative days about specific issues rather than formal courses and that it would be preferred to organise these meetings during animals' markets.

Regarding the communication of bTB test results, differences emerged between the two study areas. In Catalonia, it was described by farmers and veterinarians as adequate {S42, S43}; while in Andalusia a general perception of low feedbacks on test results was reported and both farmers and private veterinarians demanded easier and more flexible procedures to get all needed information on lab results {S44, S45}, results of the post-mortem inspections and the cultures {S46}.

Role of Wildlife and Other Domestic Reservoirs

The existence of bTB wildlife reservoirs was mentioned as a major obstacle for bTB eradication in Andalusia and Catalonia, but was especially highlighted in those areas with high prevalence and extensive herd management in Andalusia. Different opinions on the role of wildlife reservoirs arose; some people attributed a secondary role in the maintenance of the disease to these species while others were of the opinion that wildlife reservoirs could represent a primary source of infection for cattle {S47–S48}.

In general, controlling bTB in these animals was perceived as a very difficult task and several people expressed the hope of having a vaccine in the future to control the disease in these animals. The development of biosecurity plans to reduce the risk of transmission from wildlife to cattle was also mentioned. However, different views were expressed and some people considered it possible, whereas others considered it impossible to prevent cattle and wildlife interaction {S49}.

Other factors that in the opinion of some people increased the risk of bTB transmission was related to hunting activities and the lack of biosecurity, as different groups of dogs, vehicles, people, etc., interacted with infected wild animals and could spread the disease to other places {S50}. In this regard, farmers and veterinarians agreed on asking for more controls in wildlife, especially in hunting farms as they are managed as livestock farms {S51–S52}.

Several interviewees negatively perceived the supplementary feeding for hunting purposes, as it was linked to an increase of wildlife population and as a consequence an increased risk of infection for cattle herds. Moreover, the economic benefits provided by hunting activities was suggested to lead to the establishment of several mixed farms (wildlife and cattle), therefore, increasing the risk of bTB transmission. In this sense, the importance of the coordination between the different governmental statements responsible to manage animal health and the environment was highlighted {S53}.

In relation to other bTB domestic reservoirs not subjected to any control programme, the potential role of goats, sheep, and extensively reared pigs (the latter particularly in Andalusia) was mentioned. The interviewees reported that sharing pasture by cattle and these other domestic reservoirs poses another risk of infection for cattle and complained about the lack of specific legislation for this matter.

Perception on Social Aspects

Although the relationship between farmers was considered to be good, bTB was described as a sensitive issue that is normally avoided in their talks. In some occasions, conflicts between neighbouring farmers were generated to the perception that the adjacent farm was responsible for the bTB infection of the herd as the neighbouring farmer has not complied with the eradication programme and has been the source of the outbreak {S54, S55}.

The relationship between farmers and private veterinarians was described as good as in general, it is an enduring relationship and farmers tend to have a very high confidence on them {S56}. However, the existence of a "patronage relationship" between some farmers and private veterinarians was also mentioned, because private veterinarians conduct in the farm other duties than only the bTB testing that are paid by farmers. This fact could generate pressure on private veterinarians, which might not always act with professionalism as could be strongly influenced by the consequences for farmers due to the bTB control measures and for the fear of losing "customers" {S57}. In this regard, some of the interviewees also mentioned that sometimes the pressure faced by veterinarians generated conflicts, as the most rigorous veterinarians were not well accepted by all farmers {S58, S59}. In this sense, to have a greater support from the official veterinary services was perceived as a way to reduce pressure to private veterinarians {S60}.

There were different opinions about the relationship between official veterinarians from LVSs and private veterinarians and farmers. Some people reported to have a close and effective relationships and a good coordination with them, despite official veterinarians have the role to control and inspect them {S61, S62}. Others described the relationship as tense and of mutual mistrust. Main reason for this difficult relation was due to the perception of fraudulent activities with bTB testing.

The existence of fraudulent practices was acknowledged by some farmers, however, they also argued that, even though not all farmers act the same, they are all treated the same way, and they perceive that the official veterinary services are treating all of them as "delinquents" {S63, S64}.

Concerning the fraudulent practices, the missed communication of animals with doubtful test results and the non-rigorous reading of the SIT were the most reported by both farmers and veterinarians {S65, S66}. These behaviours contributed to generate demotivation especially among farmers but also among veterinarians {S67, S68}.

Risk Perception on bTB and Benefits of Eradication

Some differences arose between groups on the perceived burden of the bTB. Official and private veterinarians acknowledged both the health and the economic impact of the disease. They emphasised that animal health is the base of the development of the livestock sector and it is fundamental to an efficient animal production and, therefore, to food security and human health {S69}. The group of veterinarians expressed the need to eradicate bTB also because it represents a public health problem, not only because of the obvious trade benefits but also because of the positive repercussions on animal health {S70}.

On farmer's point of view, bTB is not seen as an important animal health problem. Most of the farmers perceived that benefits of eradication were mainly commercial, as bTB was not considered having an impact on public health neither a disease causing production losses. The fact that the meat from infected animals can be passed as "fit for human consumption" after the removal of the affected tissue (unless the carcass is generally emaciated and the lesions are generalised) generated doubts about the public health implications of bTB {S71–S73}. Moreover, they strongly disagreed that veterinary services focus so much on bTB instead of controlling other diseases that they consider more severe for human health {S74}.

Generally, farmers did not perceive any production losses due directly to bTB and some of them referred that bTB does not affect animal at all. Only few farmers perceived a direct relationship in the long term between the productivity of animals and the presence of the disease {S75, S76}. In this sense, veterinarians admitted that due to the early detection of the disease, most infected animals do not develop lesions and, in this context, it is difficult to make farmers aware on the impact of the disease {S77}. Thus, farmers mainly perceived the control of bTB as an imposition rather than a necessary activity to protect their animals {S78, S79}. They also mentioned that few studies have been done so far to quantify production losses due to bTB in the current epidemiological context and asked for updated scientific evidence on it. Nevertheless, the economic impact of the disease was strongly underlined by all interviewed groups and the commercial consequences of being bTB positive were perceived as worrisome {S80}. It was reported that some farmer abandoned the sector due to economic cost faced for the control of bTB. This is because, despite the fact that the central veterinary service provides the diagnostic tests and current law provides for indemnity for slaughtered cattle, farmers assume the rest of the costs, mainly due to restrictions on trade and animal movements and field activities for the routine screening (i.e., Vetrinarian for screening, extra-personnel for animal management, derived damages on animals) {S81}.

With regard to the amount of the indemnification, veterinarians generally opined that it is adequate and that increasing indemnity payments would mean rewarding the maintenance of the disease; they also reported that no significant complaints have been received from farmers {S82, S83}.

Future Perspective and Proposed Changes to the Programme

Most of the interviewees were sceptics on the possibility of eradication mainly due to the presence of wildlife and other domestic reservoirs. The possibility of maintaining the disease at low levels was seen as the more realistic option but it was conditioned to the existence of a stable regulation {S84}.

Some farmers also doubted about the need of so restrictive measures (slaughter of positive animals, movement restrictions, etc.) taking into account the possibility of developing a vaccine for cattle {S85}. Others would prefer to live together with the disease rather than applying such restrictive measures that, on their opinion, will end up penalising the cattle industry in the country {S86}.

Suggestions and changes proposed to the programme were related to the main problems highlighted, for example, more investigation on diagnostic test, to improve the control on fraudulent activities, to increase the personnel of the LVSs and the implementation of controls plan also on other reservoirs and wildlife.

DISCUSSION

The continuous evaluation of the bTB programme, in order to identify limitations and modifications needed, requires taking into account the "*non-biological*" context, as it might influence the effectiveness of the eradication plan (16). However, despite the acknowledged importance of these "non-biological" factors, few studies have attempted to evaluate them (38–41) and they have mainly used structured questionnaires.

In this study, we used a qualitative approach in order to identify social aspects that may influence the effectiveness of the Spanish bTB eradication programme. The use of qualitative methods, such as the semi-structured interviews that we used in this study, might have some advantages in relation to the use of structured questionnaires for these types of studies. The main advantage is the fact that they allowed to develop long conversations through which people could describe their personal experiences and opinions in their own words. This generates a discourse that is neither fragmented nor pre-coded, as it happens with structured questionnaires (42). However, it is worth taking into account that qualitative interviews (as well as surveys) can inform on what people say they do, but not what they actually do. These means that the objectively knowledge about their daily practices and perceptions would require the use of other techniques, such as participant observation or systematic observation methods (43). In order to reduce this bias, in-depth interviews were conducted always in private and started with general "warm-up" questions. In this way, we intended to generate an atmosphere of conversation rather than of interview, maximising, therefore, the possibility of achieving honest answers.

A disadvantage of qualitative interviews is that they do not allow making a direct inference of results to the whole population as the number of samples is normally low and the type of sampling is not random. However, this was not the objective of this study as we intended to know the main arguments that are circulating in the study population. In this context, the use of purposive sampling can ensure representativeness and diversity in the obtained results since it allows incorporating people of all possible typologies relevant to the research. This kind of sampling is the most effective technique when one needs to study a certain cultural domain or to explore all existing opinions circulating in the study-populations (44).

Considering both study phases, the main stakeholders involved in the Spanish bTB eradication programme were included in our study. We interviewed cattle farmers (beef, dairy, and bullfighting); Researchers with experience on bTB; Veterinarians working in the diagnostic labs: with responsibilities in the performance of the tests (gamma interferon, culture, etc.) that are performed in the bTB eradication programme; Private veterinarians who conduct bTB testing; and Official veterinarians working at different levels:

(i) Autonomous community level (regional veterinary authority) with responsibilities in the coordination of the programme in their autonomous community. These veterinarians, together with official veterinarians of other autonomous communities, also participate in the technical meetings organised at national level to review and discuss the bTB programme;
(ii) County level: with responsibilities in the coordination of the programme in their area.

Although it is true that some stakeholder profiles are missing, for example, we did not included veterinarians working in the slaughterhouses, trading partners, or consumers; however, we have included representatives from the groups most involved in the implementation of the National bTB eradication programme. Therefore, we believe that the results of this study may have a wide applicability as we have gained information on the main discourses.

Overall, 52 people were interviewed (13 people for exploratory and 39 for in-depth interviews), among those there were 22 veterinarians and 30 farmers. The selected number of participants relied on previous studies based on grounded theory and wanted to maintain a balanced emphasis between the homogeneity (requiring smaller size) and the heterogeneity (requiring larger size) of the sampling target (45, 46). In the case of farmers' selection, the size of herds, the production type, and bTB prevalence at county level were taken into account; while, in the case of veterinarians, the years of experience working with the bTB programme, their roles and responsibilities at the workplace and the disease prevalence at county level were considered. Doing this, we wanted to avoid failures in capturing insights, experiences, and activities and, therefore, achieve the theoretical saturation of data (45).

In recent years, the application of ethnographic methods has been extended to the description and analysis of social relations within any group of people: social, professional, or conceptual (47), making this strategy of analysis particularly suitable for our study. Moreover, this methodology is optimal if people to interview tend to disguise their way of acting and/or thinking, as could be the case in the bTB eradication programme.

One of the main results of this study was an apparent lack of motivation of some stakeholders and a general feeling of distrust in control measures and disbelief in test results. The complexity of the disease combined with gaps in knowledge and the lack of an efficient communication about the interpretation of diagnostic test results and control interventions seems to be important causes of disbeliefs, which in turn might generate different kinds of guesses and interpretations. Good communication and coordination between the different stakeholders have been previously described as having paramount importance in any health programme, since it might be a critical factor for the success of bTB control interventions (39, 40). The implementation of official communication plans on bTB and the selection of the most appropriate strategy would be an interesting research topic to tackle. Moreover, our results also points out the importance of informal places for discussion and solving doubts and the primary role of private veterinarians influencing farmers' opinions.

Similar to our findings, Calba et al. (39), in a study conducted in Belgium, reported the key role that private veterinarians have in the surveillance and communication with farmer; they found that private veterinarians are under pressure of their client (farmer), making necessary a greater support by the official veterinary services, and highlighted the importance to address such issues in order to improve the acceptability level of the bTB surveillance system. In agreement with Calba et al. (39), we found that the lack of support by the official veterinary services has mostly likely contributed to the feeling of distrust towards official veterinarians, to the absence of adequate infrastructures to perform the SIT, and to the pressure faced by private veterinarians.

Perceived inaccuracies in bTB detection increased mistrust and demotivation, especially among farmers. Discordant results between diagnostic tests, the lack of guides and standards for interpretation of diagnostic results and the absence of lesions at the *post-mortem* inspection have been already described as possible barriers toward bTB eradication in previous studies, as they might reduce the engagement of farmers in preventive health interventions (4, 8, 39). Our results further highlight that the level of confidence on the interpretation of SIT results was often linked with skills and experience of official and private veterinarians involved in the field activities of the testing campaign.

Along these lines, since expert estimations of the risk of bTB contain many and high levels of uncertainty, it is perfectly rational for farmers not to limit themselves merely to these estimations when evaluating the magnitudes of risks, as stated by some scholars (48, 49). It is, therefore, logical to also ask about such issues as how much trust the institutions involved in risk management deserve: "I have argued that public perceptions of and responses to risks are rationally based on judgements of the behaviour and trustworthiness of expert institutions, namely those that are supposed to control the risky processes involved" (49). The results of our research seem to fit well with this hypothesis, as far as public and private institutions in charge of tuberculosis control are implementing actions perceived as ambiguous or not always coherent by the farmers.

The lack of the application of sanitary measures to wildlife, goats and pigs in extensive farming systems were pointed out and it was perceived as a comparative grievance to what is done in cattle, as measures on cattle were perceived as much more strict. In this regard, all groups asked for improvement in coordination between institutions and implementation of specific measures and better management of wildlife, especially for hunting farms. In this regard, it is worthy to mention that recently it has been launched a reinforced surveillance programme for bTB in wildlife named PATUBES (34) which was not known by the interviewers as it was not publically available at that time. Thus, it would be worthy to update opinions and beliefs in the future in the light of the results of this reinforced programme.

In relation to other domestic reservoirs, the Spanish bTB eradication programme only includes the testing in goats that are epidemiologically related to infected cattle herds, and sheep and extensive pigs are not included in the programme. With the exception of goats (33), the role of sheep and pigs in bTB epidemiology is still controversial, but some stakeholders had the perception that they are important reservoirs. In this sense, more research might be needed in order to communicate effectively their role to the different stakeholders.

Some other factors also mentioned in this study such as some non-specific SIT reactions in young animals might also need further research in order to fill gaps and enhance communication.

Moreover, farmers perceive very few benefits of being bTB free and that the economic impact of the disease is due to its control rather that to its presence. In addition, a low awareness on the zoonotic risk of bTB also emerged; these aspects might discourage farmers in implementing preventive measures against bTB since the cost for such implementation would outweigh perceived benefits. This perception might be another major factor influencing the effectiveness of the programme as preventive measures might be undertaken by farmers if they clearly perceive that the benefits outweigh the costs (4).

The lack of enough human resources for bTB activities, as reported by the group of official veterinary services, might also deserve further attention. The support of official veterinary services to private veterinarians beyond official control inspections could help to enhance relationships and communications between groups.

CONCLUSION

The use of a qualitative approach, allowed us to catch specific information related to the local context and highlight aspects that could be missed by applying quantitative epidemiological methods. Our findings represent a good part of the probable sphere of perceptions, opinions, behaviour, attitudes, and knowledge of the study population and several key critical points that may hinder the success of the bTB eradication programme in Spain were identified.

Major issues were related to the perception of the bTB programme as a law enforcement duty and to the lack of an adequate motivation, as a general feeling of distrust towards official veterinary services was expressed. The improvement of communication strategies should be considered as a priority, as it seems to be a major factor influencing the trust between stakeholders and the effectiveness of the eradication plan. Lack of understanding of test results and control measures, lack of perceived benefits of being bTB free, gaps on knowledge together with the complex epidemiology of bTB deserves further efforts on communication. Private veterinarians had a major role in influencing farmers' opinions but their feeling of inadequate support from veterinary services should be taken into account.

These results can be extremely useful to develop some context-dependent recommendations and interventions in order to increase the acceptability of the bTB eradication programme and ensure its proper implementation.

ETHICS STATEMENT

Ethical approval was not required for this study, in accordance with the national and institutional guidelines, as it did not include samples or experiments on people but only their expression of opinions in relation to a specific topic. With regard to the informed consent of participants: as the interviews were anonymous, the data were analysed anonymously and the decision to participate in the study was solely up to each contacted person, we did not consider it necessary to obtain a written consent. We orally informed all participants of the elements of consent and permission was obtained verbally before starting the interview. At the beginning of each interview: interviewers introduced themselves and the contacted person was informed on the study design and its objectives. It was explained that the participation was voluntary and completely anonymous (data collection and analysis) and that they could stop the interview at any time. It was explained that there were no expected risks and no expected personal benefits associated with participation in the study. We also asked their approval for using information collected through the interview and for using direct quotes from them and these would only be cited as from a "farmer" or "veterinarians," keeping the anonymity.

AUTHOR CONTRIBUTIONS

Conceived and designed the study: GC, AA, and JE. Performed and transcribed qualitative exploratory interviews: GC, AA, SN, and JC. Performed and transcribed qualitative in-depth interviews: PI, EC, and SL. Analysed collected data: GC, AA, PI, EC, and SL. Wrote the paper: GC and AA. Revised the paper: AA and JE.

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SUPPLEMENTARY MATERIAL

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Animal Welfare and Economic Aspects of Using Nurse Sows in Swedish Pig Production

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The number of born piglets per litter has increased in Swedish pig industry, and farmers are struggling to improve piglet survival. A common practice is to make litters more equally sized by moving piglets from large litters to smaller to make sure that all piglets get an own teat to suckle. Litter equalization is not always enough, as many sows have large litters and/or damaged teats, which results in an insufficient number of available teats. One way to solve this problem is to use nurse sows. A nurse sow raises, and weans, her own piglets before receiving a foster litter. The objectives of this study were to address how the use of nurse sows affects the welfare of sows and piglets and to explore how it impacts the contribution margin of pig production in Sweden. A literature search was made to investigate welfare aspects on sows and piglets. As there were few published studies on nurse sows, an expert group meeting was organized. In order to explore the impact on the contribution margin of pig production, a partial budgeting approach with stochastic elements was used for a fictive pig farm. Standard templates for calculating costs and benefits were supplemented with figures from existing literature and the gathered expert opinions. In Sweden, the minimum suckling period is 28 days while published studies involving nurse sows, all from outside of Sweden, weaned the piglets at 21 days. A Swedish nurse sow will thus get longer lactation period which might increase the risk of poor body condition, damaged teats, and shoulder ulcers. This indicates a reduced welfare of the sow and may lead to impaired fertility and increased culling risk. On the other hand, the piglet mortality could be reduced with the use of nurse sows, but the separation and mixing of piglets could be stressful. The partial budgeting suggested that the nurse sow system is slightly more profitable (+6,838 Swedish krona) per farrowing group during one dry and one lactation period compared to the conventional system. The result is, however, highly dependent on the input values, and welfare aspects were not considered in the calculations.

Keywords: piglet, pig industry, modeling, contribution margin, stochastic simulation

INTRODUCTION

Breeding programs toward hyperprolific sows have resulted in sows that produce a surplus of piglets compared to the number of functional teats (1). The Swedish national average of live-born pigs per litter has risen from 13.1 to 14.0 from 2011 to 2016 (2), and the average litter size is expected to rise even further. The intention with the increased litter size is a more efficient and profitable pig production by a higher number of piglets that can be weaned and later slaughtered, without increasing the number of sows. However, in large litters more piglets will have to share the resources (e.g., milk), and a sow usually has 14 teats and can thus feed up to 14 piglets. In today's production, a sow can give birth to more than 20 live-born piglets. If no action is taken, not all of these piglets can be expected to survive.

Most often farrowing occurs batch wise, i.e., a whole group of sows farrows within a few couple of days. This makes it possible to move piglets from large litters to sows with smaller litters, known as "litter equalization" (1). In this manner, the survival rates might increase (3). If the number of functional teats in the farrowing group is not sufficient, surplus piglets can be gathered and placed with a nurse sow. A nurse sow is a lactating sow from another farrowing group that have just weaned her own litter (4). The nurse sow is moved into the group of fresh sows and will continue to be suckled by a new litter of foster piglets. Nurse sows can be used in one-step or two-step systems (1). A one-step system means that a sow, immediately after weaning her own piglets, is moved to a foster litter with newborn "surplus piglets". The one-step nurse sow will have a total lactation period of at least 8 weeks (28 + 28 days) under Swedish conditions. Another way to use nurse sows is to do it in two steps. In this way two sows are needed. Sow 1 nurses her own litter for 4–8 days and then the whole litter is moved to Sow 2, which has just weaned her own litter. Sow 1 receives newborn surplus piglets and nurses them for at least 28 days if in Sweden. Sow 1 will have a total lactation period of approximately 5 weeks (4–8 + 28 days) which is comparable to the average lactation period in Sweden [33 days (2)]. Sow 2 will have a prolonged lactation period of approximately 3 weeks depending on how old the foster litter is when it is moved. If the foster litter is 4 days when transferred, the nurse sow needs to have them for at least 24 days before they can be weaned. This gives a total minimum lactation period of 7.4 weeks (28 + 24 days) for Sow 2 if she weaned her own litter after 28 days. The overall lactation period for the nurse sows is shorter in the two-step nurse system. Older foster piglets are also more easily accepted compared to newborn by sows at weaning (5). The two-step nurse system is known to be more commonly used in Denmark where nurse sows are used to a wide extent (6).

The Swedish legislation has more stringent rules regarding the keeping of sows and piglets during suckling than the European Council Directive (7). Sows in Sweden should be loose housed at both farrowing and suckling (SJVFS 2010:15), which is not a requirement in the rest of the EU where the sows can be kept in crates during this period (7). Furthermore, in Sweden, piglets have to be at least 28 days at weaning. This is generally valid throughout the EU, but an exception to the regulations makes it possible to wean piglets already at 21 days, which is widely practiced in nurse sow systems in order to limit the overall lactation period for the nurse sow (1). This means that nurse sows in Sweden will have longer lactation periods compared to nurse sows in other countries, and this may have an impact on their welfare, but the welfare aspects of nurse sow systems in Sweden have not been addressed so far.

There are also no published studies on the economic aspects of using nurse sows under Swedish production conditions. The objectives of this study were therefore to: (1) discuss possible animal welfare consequences associated with using nurse sows under Swedish conditions, with a standpoint from available published literature and expert opinions and (2) evaluate the effects of using nurse sows on the contribution margin of piglet production in Sweden.

MATERIALS AND METHODS

As there is a paucity of literature on nurse sows, and no published studies from Sweden, an expert group meeting was organized to gather information on the nurse sow system and its effects on animal welfare and production parameters. This information was a necessary first step to build an economic model as results and figures from available literature could not be directly transferred into the economic models as the Swedish production conditions differed in many ways. The expert group meeting was arranged in Uppsala, Sweden, in August 2016 and included persons from the industry working as herd health veterinarians, production advisors, and researchers. The meeting started with a brief presentation of the results from a literature review consisting of 36 references including published papers, scientific reports, and a bachelor thesis. Different animal welfare aspects of using nurse sows on herd level as well as individual level, both from the sow and piglet perspective, were then discussed according to a structured protocol. In the next step, the economic parameters included in a standard template (8) were discussed one by one. Finally, the group agreed collectively on which input variables to include in the economic model for this study as well as their effects. The expert group meeting lasted for 3 h.

To estimate the economic aspects of using nurse sows, a partial budget (contribution-margin)-based stochastic farm-level model was developed in Microsoft Excel 2013 (Microsoft Corp., Redmond, WA, USA). In this way, we could isolate the effects on the contribution margin of using nurse sows compared to a conventional system, by only focusing on the economic variables (revenue and costs) likely to depend on the system. The model was based on a standard template (8), but modified according to experts' opinions to include most variables affected by using nurse sows. Input variables were based on Swedish pig production data from 2015 and 2016 (9) and the results from the expert group meeting. The input variables are listed in **Tables 1** and **2**.

The model scenario was based on a farm with three farrowing stalls and farrowings fortnightly. The conventional system had 590 sows/year, and the nurse sow scenario had 567 sows/year. Each farrowing group was kept in stalls with 50 farrowing pens. In the conventional system 50 pregnant sows were housed in the pens at start, while in the nurse sow scenario 48 pregnant sows were housed and the remaining 2 pens were used for surplus piglets, and two-step nurse sows (from another farrowing group) were later moved to these pens. The sow groups were moved to the farrowing unit 4 days before expected farrowing and kept in that unit until all piglets had reached 28 days of

TABLE 1 | Overview of stochastic input variables used in the partial budgeting model.

Input variable	System	Mean (SD)	Mode; min; max	Distribution	Reference
Number of live-born piglets per litter	Both	13.7 (0.8)		Normal	(2)
Piglet mortality rate (deaths/100 piglet-years)	Conventional		0.18; 0.08; 0.33	Triangular	WinPig and expert opinion
	Nurse sow		0.14; 0.07; 0.25	Triangular	Expert opinion
Weight at sale (79 days)	Conventional	31 (3)		Normal	(2)
	Nurse sow	31 (2)		Normal	Expert opinion
Feed consumption during lactation (MJ per week)	Both		510; 490; 530	Triangular	TN-70 feed recommendation, 2016
Feed consumption during dry period (MJ per week)	Both		220.5; 245; 269.5	Triangular	TN-70 feed recommendation, 2016

TABLE 2 | Overview of deterministic input variables used in the partial budget model of economic consequences of using nurse sows.

Input variable	Fixed	Reference
Price at sale [Swedish krona (SEK)/79 days old piglet]	580	HK Scan, 2016
Additional bonus at sale if piglet batch weight > 30 kg (SEK/extra kg)	6	HK Scan, 2016
Feed consumption piglet (kg/week)	1	Expert opinion
Price of feed during lactation (SEK/MJ)	0.22	(10)
Price of feed during dry period (SEK/MJ)	0.20	(10)
Price of piglet feed (SEK/kg)	6	
Semen costs (SEK/unit)	40	(11)

age. In this way, the sow group stayed in the farrowing unit for a 5-week period.

The basic model was deterministic, however, some key variables were modeled stochastically (**Tables 1** and **2**). A stochastic model takes the parameter variation into calculation to generate results with a distribution, representing uncertainty in results (12). The stochastic elements of the model were handled with @RISK 7.5 (Palisade Corp., Ithaca, NY, USA), an Excel add in, which performs risk analysis using Monte Carlo simulations. In each simulation, 5,000 iterations and Latin Hypercube sampling were used with a static seed of 31,517 to ensure that all simulations provided repeatable results.

The output variables affecting the contribution margin in the partial budgeting were "Revenue from sold piglets," "Feed costs", and "Semen costs." "Revenue from sold piglets" was calculated by using the number of weaned piglets per farrowing group (the number of live-born piglets per farrowing group × piglet mortality rate) and the price at sale [580 Swedish krona (SEK) per 30 kg batch-pig weight with an addition of 6.5 SEK per kg for batches with average weights > 30.1 kg/pig]. "Feed costs" consisted of the number of feed weeks × feed consumption × feed price (for all categories, i.e., sows in dry period, lactating sows, and growing piglets). "Semen cost" was calculated as the number of sows × cost for semen. A correlation between number of live-born piglets and piglet mortality rate for the conventional system and the nurse sow system was set to 0.8 and 0.5, respectively. The impact on contribution margin (revenues minus costs) of using nurse sows was compared to a conventional situation and was calculated at batch level for one farrowing group (50 pens) from insemination (included one dry and one lactation period). The full economic model is shown in Table S1 in Supplementary Material.

Further contact was made with the expert group to sort out upcoming queries and to validate the model. Finally, a sensitivity analysis was used to evaluate input variables with strong impact on the model outcome. This was conducted using the sensitivity analysis function of @Risk. Regression tornado diagrams, in which @Risk runs a multiple regression analysis for each iteration with the outcome of interest and the simulated (standardized) values of the stochastic variables as independent variables, were carried out. This analysis shows the mean of the 10% lowest and highest simulated values (Tornado graph "change in output mean") and the change in the outcome variable when the independent variables increase by 1 SD with all other variables being constant (Tornado graph "regression mapped values").

RESULTS

Welfare and Production Aspects

During the expert group meeting, the participants concluded that consequences of being a nurse sow will be highly dependent on the farmers' skills in selecting appropriate individuals. Parity, lactation stage, maternity traits, and robustness of the nurse sow will be of major importance.

An early separation will most likely cause negative stress, both for the sows and for the piglets (13). In the first few days after farrowing, the teat order is established as each piglet has a particular pair of teats to suckle (14). In litter equalization, foster piglets are mixed with the sow's biological piglets, and this might start a fight over the teats. In the case of late litter equalization, the suckling is affected negatively, as the fighting piglets make the sow restless, which results in more disrupted nursings and deficient milk ejection (15). In the two-step nurse sow system, all the sows' biological piglets are removed. In this way, the teat competition might be less severe as all in the new litter are foster piglets (5). In a recent study by Amdi et al. (16), no differences in suckling frequency between nurse and non-nurse sows could be detected. This indicates that being a foster piglet in the nurse sow litter might be similar or less stressful than being exposed to litter equalization which is a common practice in Sweden.

Several studies have shown that it might take up to 12 h before the nurse sow accepts the new litter and allows the foster piglets to suckle (5, 17, 18). Generally, two-step nurse sows are considered to accept the foster piglets quicker compared to nurse sows in the one-step system (5). It can take over 12 h before the sow allows the foster piglets to suckle and in some cases the nurse sow never accepts the foster litter (19). Thorup and Sørensen (5) compared nurse sows in the one-step and two-step systems, and seven of eight sows let the foster piglets to suckle within 12 h if they had nursed their own litter for 1 week and then received newborns (Sow 1 in two-step systems). Of the sows that received newborns after 3 weeks of nursing her own litter (one-step system), only three of eight sows allowed the foster litter to suckle within 12 h. This period of starvation affected the piglet mortality in the foster litters. Mortality was 6% in sows allowing them to suckle within 12 h compared to 20% in litters where it took over 12 h. However, the risk of starvation (and eventually death) is high also in the conventional system if the litter size exceeds the number of functional teats. In cases where the sow accepts the foster litter, mortality risks in foster litters are not higher than those seen in conventional litters. Bruun et al. (20) found that non-nurse sows on average weaned 11.65 piglets/litter, while nurse sows weaned 12.41 piglets in their own litter and 11.48 piglets in the foster litter. Moreover, the animal welfare-related consequences for piglets in nurse sow systems are assumed to be similar to what have been reported from other countries, as the moving of piglets occurs at the same time after birth regardless of the total length of the suckling period.

The majority of the nurse sow studies have been carried out in countries where sows are kept in farrowing crates throughout the suckling period. Since a loose-housed sow has a greater ability to move around, and thus more easily can avoid the foster piglets, it is possible that it takes even longer time before loose-housed sows nurse the foster litter. This imposes greater challenges for the foster piglets in nurse sow systems in Sweden. In a Swedish study by Nilsson and Larsson (21), only 2 of 18 nurse sows (11%) allowed the foster litter to suckle within 6 h. Twelve nurse sows (67%) allowed them to suckle after 6–12 h, and four sows (22%) allowed the foster piglets to suckle after 12 h. This time of starvation will have a negative effect on the piglets and might cause death in weak piglets.

Furthermore, an extended lactation period may deplete the sows' body lipid and protein reserves and cause damaged teats. A low body condition score increases the risk of shoulder wounds (22) and impaired fertility (23). A cross-sectional study conducted in 57 sow herds in Denmark showed that nurse sows had significantly higher prevalence of udder wounds and swollen bursa on legs compared to conventional sows (6). There were, however, no differences in body condition or prevalence of shoulder ulcers. This could be due to that farmers scored body condition as one of the most important factors when choosing a nurse sow. As the overall lactation period for a Swedish nurse sows can be as long as 8 weeks, due to our strict animal welfare regulation regarding weaning age, loss of body condition is very likely to occur. Selecting sows with a good body condition score, therefore, seems to be equally or even more important under Swedish conditions.

Several studies have shown that the interval between weaning and conception is longer for nurse sows (20, 21, 24). In a study by Bruun et al. (20), based on data from nearly 80,000 litters, the nurse sows (defined as Sow 2 in a two-step system) had 4.23 days between weaning to conception compared to the 4.19 days found in conventional sows. The nurse sows in that study had an average lactation length of 40.3 days versus 27.8 days for the conventional sows. There was, however, no difference in the rate of sows returning to estrus.

The temporary prolonged nursing interval that arises when separating the sow from her own litter and before accepting the new foster litter has been shown to be sufficient to induce heat in some individuals (24). In these cases, the sow gets unsynchronized with the rest of the farrowing group, which can cause problems in the batch-wise production. Furthermore, loss of body condition in sows and a long period of starving before the nurse sow accepts the foster litter and allows piglets to suckle were considered as the main risk factors for reduced welfare under Swedish conditions.

Economic Aspects

The economic model demonstrated that the contribution margin was slightly improved in the scenario with nurse sows compared to the conventional situation. The mean contribution margin in the conventional system and the nurse sow system was 232,448 SEK (SD = 16,586) and 239,286 SEK (SD = 23,733), respectively, for one farrowing group with 50 available pens followed during one lactation and dry period. The differences between the systems ranged from −74,880 to 95,552 SEK with the mean value of 6,838 SEK (SD = 27,773). The nurse sow system was beneficial compared to the conventional system in 58% of the iterations.

In **Figure 1**, the sensitivity analysis tornado diagram shows that piglet mortality, number of live-born piglets, and weight at sale had the greatest impact on the results. The other inputs in the model had minimal impact. The tornado graph in **Figure 2** demonstrated that piglet mortality and weight at sale had greatest impact on the contribution margin when the independent variables were increased by 1 SD. For instance, the benefit of using nurse sow system increased as the piglet mortality rate in the conventional system increased by 1 SD, and the opposite scenario was seen when piglet mortality rate increased in the nurse sow system. Changing the price at sale with +10% resulted in a higher contribution margin (7,308 SEK) and reducing the price at sale with −10% reduced the contribution margin (6,368 SEK) slightly. The nurse sow system was, however, favorable in both scenarios.

DISCUSSION

The objectives of this study were to discuss the animal welfare aspects and to explore the economic aspects of using nurse sows in Swedish pig production. The results suggest that there are animal welfare concerns both for sows and piglets that need to be considered and also that using nurse sows can provide a slightly better economic performance than conventional practice on Swedish farms. However, it should be noted that in the economic model, the definition of contribution margin did not include cost items related to salary and veterinary costs, as these variables are considered relatively constant in the short run. Veterinary costs at pig farms in Sweden are usually constant because almost all farms have a fixed number of scheduled veterinary visits per year and need then not be included in a contribution margin analysis (which is conducted within the limits of given fixed resources). Salary was not added to the model

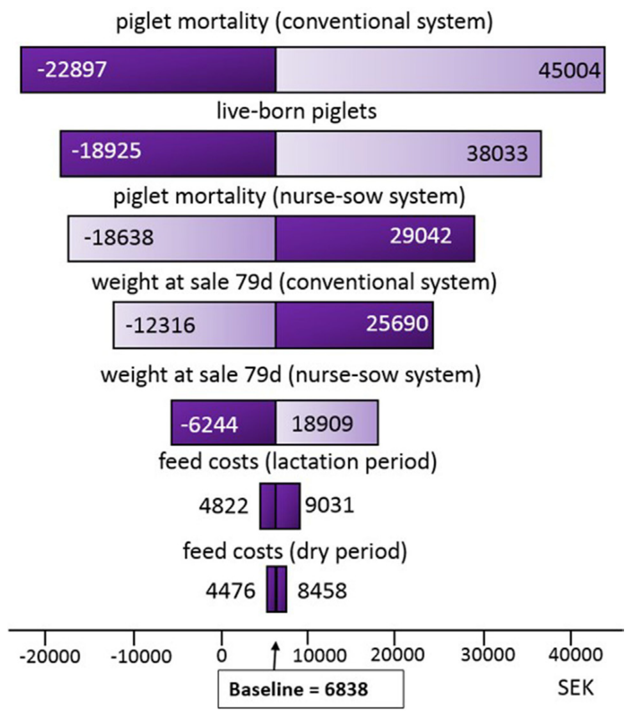

FIGURE 1 | The input variables with greatest impact on the partial budget analysis comparing contribution margin of a nurse sow system with a conventional system. Values on either side of the bar represent the mean of the 10% lowest and 10% highest simulated values in Swedish krona for each variable.

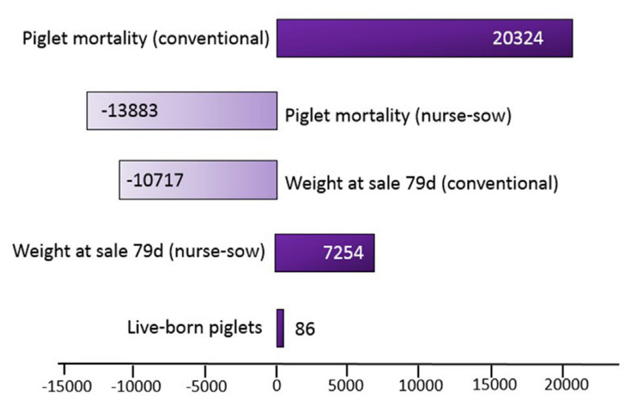

FIGURE 2 | A tornado graph (with regressed mapped values) demonstrating the change in contribution margin (Swedish krona) if the input variables are increased by 1 SD and the other variables are held constant.

as the amount of person-hours needed in the analysis was too difficult to estimate, because only a bachelor thesis on labor use in nurse sow systems in Sweden has been done. Moreover, labor is a production factor that in reality can be considered fixed in the short run, as it usually takes time to recruit new employees and it could be difficult finding persons interested in part-time employment, and should then by definition not be included in the calculation of contribution margin. Furthermore, the animal welfare implications are not included in the economic model, even though there are several important animal welfare aspects regarding both sows and piglets. Direct economic effects of such aspects are, however, difficult to assess and research into ways to transform ethical values into monetary terms is strongly advocated.

The general goal with nurse sows is to increase the piglet survival rate (from birth to weaning). In our scenario, the mortality rate was set to be higher in the conventional system, an input which was based on the expert solicitation exercise because no studies were available. The sensitivity analysis showed that this variable had the largest influence on the outcome, and it would therefore be important to estimate piglet mortality in nurse sow systems, especially under Swedish conditions, to verify our results. The second most influential variable was number of live-born piglets, but the input value of variable was based on large number of production records, and the sensitivity analysis thus shows the effect of an inherent variability.

It is important to remember that there is a large variability in most input variables on commercial farms, and the results from this study only give an indication that the nurse sow system can be profitable under average Swedish production conditions. The beneficial potential of using nurse sows will highly depend on the conditions and management routines at specific farms. The economic model in this study included only a few number of variables. Parameters not included in this economic model, e.g., labor, may influence the results, and a cautious interpretation of the results is recommended. There could also be other important welfare aspects (e.g., behavioral and physiological parameters), additional to the ones discussed in this paper, which need to be considered in future studies.

CONCLUSION

Using nurse sows is one way to reduce piglet mortality rates from birth to weaning. The Swedish national average of live-born piglets is 14.0 per litter. Breeding toward larger litter sizes will result in lower average birth weights for piglets, but also to an increased risk of non-sufficient colostrum intake because of the competition for functioning teats. This study explored the animal welfare and economic consequences of using nurse sows under Swedish production conditions to overcome some of these problems. In the nurse sow system (assuming a fixed number of farrowing pens), there will be less sow-years compared to the conventional situation. The partial budget analysis showed a higher contribution margin for the nurse sow system. Animal welfare aspects were, however, not included in the economic model, and due to the limited number of input variables the results should be interpreted with caution. There are important animal welfare concerns that need to be studied further, especially under Swedish production conditions.

AUTHOR CONTRIBUTIONS

All authors contributed to the design of the work. KA, HH, and RW participated in the expert group meeting. KA, HH, and UE

performed the analysis. KA drafted the manuscript, and all the authors read and approved the final manuscript.

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SUPPLEMENTARY MATERIAL

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The Value Chain Approach in One Health: Conceptual Framing and Focus on Present Applications and Challenges

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The value chain (VC) is a major operational concept for socioeconomic analysis at meso level. Widely mobilized in development practice, it is still undergoing conceptual and practical refining, e.g., to take account of environmental and social sustainability. Briefly, VC refers to a system of value creation through the full set of actors, links, technical and commercial activities and flows involved in the provision of a good or service on a market. In the past decade, this concept has been promoted in the management of animal health. In particular, the emergence of highly pathogenic avian influenza (HPAI) has triggered an interdisciplinary dynamic including VC analysis as a central tool. These efforts promoted participatory investigation methods in the analysis of health systems. Using qualitative and quantitative data, these methods acknowledge the usefulness of actors' involvement and knowledge, hence facilitating the transdisciplinarity needed for effective action. They fit into adaptive and action-oriented strategies, fostering stakeholders' participation. Recent research on HPAI surveillance in South-East Asia merged VC and participatory approaches to develop innovative tools for analyzing constraints to information flow. On-going interventions for HPAI prevention and control as well as the prevention of other emerging zoonotic risks in Africa are presently building on this VC framework to develop strategies for its application at national and regional scales. Based on the latter experiences, this article proposes a field-based perspective on VC applications to animal and public health systems, within a One Health approach responding to the overall challenge of complexity.

Keywords: livestock value chain, behavioral analysis, socioeconomic, One Health, interdisciplinarity

A COMPLEXITY FRAMEWORK OF ANIMAL AND PUBLIC HEALTH

Animal and public health issues are increasingly considered as "complex," referring to challenges as emerging zoonoses, antimicrobial resistance or environmental contamination, while ensuring food security for a growing population. These so-called "wicked problems" are strongly interconnected, tied to the rapid evolution of animal production, trade, as well as intricate and widely unpredictable epidemiological processes involving shared pathogens inside a shared and changing environment.

Considering the case of avian influenza, the wide diversity of actors across food systems at different country scales is source to diverse and even conflicting interests impacting the issue; the unpredictable virus mutations or reassortments, the involvement of wild birds in the virus spread, the unregulated poultry production and trade in many countries, and the potential for virus spillover to other species make surveillance paramount in humans, domestic animals and wildlife, in a context of weak cross-sectorial collaboration. Recognizing this "complexity" is an important step, pointing to a conceptual framework guiding practical action (1). Fitting into the theory of systems (2), complexity results from the large number of components in open systems, interwoven by non-linear and feedback interactions, as observed in epidemiological and economic relationships inside food systems. Due to emergent properties of systems, complexity calls for holistic approaches in health management, translated into transdisciplinarity, joining academic and non-academic knowledge and action to solve societal problems (3). The openness of complex systems may be exemplified by animal production intensification within poorly regulated framework: this may point to defaults in biosecurity, causing higher risk for geographic spread and zoonotic transmission. But it also refers to the uncontrolled use of antibiotics, to food contamination and environmental damage, etc. This openness means that any intention to analyze such systems in view of addressing health problems will first need a cautious framing of their boundaries, defining the limits and outreach of the proposed solutions.

This complexity framework is structuring a range of approaches in animal and public health pointing to the communality of health issues and the need for an integrated management. The most prominent concepts are probably the EcoHealth or the One Health (OH) approaches (3). To analyze health problems within the entanglement of their drivers and consequences, systems have to jointly represent interactions between humans, animals, and their environment, leading to the notion of social–ecological system and the structured analysis of their subsystems along a diversity of methods (4). Such an understanding needs a tight collaboration of multiple disciplines, among which social sciences hold a crucial role, since human behavior and governance of systems' components are central drivers of the modeled challenges (5, 6).

SOCIOECONOMIC REASONING FOR OH

The common misunderstanding of economics as being a "science counting in monetary terms" instead of "studying behavior" has restricted its contribution to a role of accountancy of disease impact and management (7, 8). Presently, the OH concept, highlighting complexity and the deficits of mono-dimensional approaches, reactivates the already identified need to question economic methods and frameworks (9). Deciphering whether certain forms of economic organization, coordination, or behavior are particularly prone to higher health risk appears now as a major scientific challenge.

This article presents the value chain (VC) approach as a typical example of socioeconomic reasoning. A particular feature of it lies in its attempt to address multiscale systems, applying its conceptual framework and tools to individuals, households, firms, communities, networks, countries, and at the international level. It considers both the influence of individuals on the group and the influence of the group on the individual, this cross-determination being a textbook application of feedback interactions inside complexity frameworks (10). As a matter of fact, VCs are complex in nature. Indeed, beyond the simplified models proposed by economists to tackle wide economic sectors, empirical research on livestock VCs shows the coexistence of interwoven subsystems encompassing various networks of stakeholders, forms of coordination and levels of complexity: informal or formal, modern or traditional, high or low technology, quality-, or price-driven chains (11).

VALUE CHAINS AND OH

Value chain is a major operational concept in business and economic literature, built upon the seminal works of Porter (12). Widely implemented in agricultural development, VCs are subject to various approaches and practical guides (13). In its widest understanding, VC refers to the full set of actors, their mode of interaction (types of agreements, relations) within strategic networks, activities (technical or economic functions), and flows (material, immaterial) involved in the provision of a good or service on a market. May also be included in the same approach peripheral actors, not taking directly part to the product or service provision, but supporting or influencing VC behaviors and strategies (14). Hence, the components of VC analysis are: mapping actors and processes, understanding governance, identifying opportunities for upgrading and improving equity (15). The overall upgrade of VC may call for changes in the legal framework and for financial or technical support, to accompany individuals in improving their process in the VC (upgrading), recentering it on a core-business (downgrading), or redirecting their activities as they are unable to cope with changes in the VC (out-grading) (16).

Considering both actors and processes inside a governance structure, VC analysis appears as a typical case of socioeconomic reasoning. Governance is here a central concept gathering all forms of coordination between actors: vertical and horizontal, internal and external. It covers the diversity of rules and frameworks influencing actors' behavior (regulatory structure, private standards, cultural norms, contracts), which all may constitute incentives for practices entailing animal and public health risks or benefits. Each actor, by contributing to the process, is contributing part of the final product/service value, termed "value added." This value creation is central to economic analysis, aiming at increasing and sharing it among stakeholders. However, the understanding and fostering of change in VC governance may pursue diverse goals, such as food safety, animal welfare, and public health, thus fitting in the OH framework (17). Recently, FAO renewed the approach proposing the concept of sustainable food VC (SFVC), extending the coverage to social and environmental dimensions of sustainability by taking account of externalities in the calculation of value added for society (18). Hence, beside any particular health focus, VC improvement increasingly calls itself for interdisciplinary research (19), e.g., to better include smallholders in sectorial growth.

The OH perspective mainly addresses animal-related VCs, i.e., livestock VC themselves and related chains of feed and health service provision, but also wildlife and bushmeat VC. These are contributing to food security, and thus to health, but are also a source of risks that have to be controlled along the chains of production, technical processes and stakeholder relations. The main risks considered are zoonoses, foodborne toxicoinfections, drug residues, and other chemical contamination. The threats to environment and their consequences for human health are also relevant problems to be addressed through livestock VCs, as highlighted in the SFVC approach. Technical approaches have long been developed for risk control through procedures under normative quality standard frameworks, as the Hazard Analysis and Critical Control Point, but these are mostly restricted to the industrial context. As exposed here below, VC approach in a OH perspective goes beyond that sole technical control to encompass a wider notion of actors' behavior and explicitly address the link to risk dynamics outside the strict processing of products.

In the past decade, the emergence of highly pathogenic avian influenza (HPAI) acted as a triggering event in the building of the OH approach, gathering first public and animal health actors in a common management of the crisis (20). These interdisciplinary efforts mobilized VC analysis as a tool to map actors, processes and value creation in order to plan HPAI control and assess the impact of the disease and control measures (21–23). In HPAI management, as in animal health in general, VC analysis was firstly used for impact assessment of diseases and/or interventions. The potential of this framework for behavioral studies in risk management and health governance appeared later (15, 24). Mainly drawing on the experiences of HPAI and Rift Valley Fever, the importance of understanding VC actors' behaviors and strategies contributing to risk production and management was progressively affirmed. Hence, further research was called for and developed, again in the framework of HPAI. Recurrently, published and unpublished works highlighted both the importance of VC analysis for health governance and safety management in the livestock sector, but also the limits of it (e.g., lack of social and spatial perspectives in most VC research) and the need for methods to evolve and adapt to the specific needs of this OH application (24–26). More precisely, participatory approaches and qualitative research have proved crucial in view of needed changes.

VCs AND PARTICIPATORY APPROACHES

Value chain analysis for HPAI control was embedded in a movement toward the use of participatory investigation methods (21, 23), thus reviving participatory epidemiology (27) and the consideration for farmers' viewpoint (28). These methods, using qualitative and quantitative data, acknowledge the usefulness of field actors' knowledge and spur actors' involvement, hence facilitating the transdisciplinarity needed for analysis and action. The wide use of visual tools in participatory approaches facilitates communication, information sharing, and joint decision-making, with an explicit goal of triggering positive changes in communities. This philosophy of action-oriented intelligence also underwent important developments in parallel in animal and public health (29, 30). Within the OH approach, community participation, supported by shared policy between environment, human and animal health, proved its efficacy in the surveillance of vector-borne diseases and zoonoses (31), while the eradication of rinderpest represented a major contribution to world food security (29).

Originating in action-research, participatory approaches emerged as a good practice in VC analysis for risk management purposes. There are two main motives for this wide adoption. First, VCs are highly variable in length, complexity, and degree of formalized organization, thus calling for flexible and non-standardized methods. The particular weight of home-consumption and direct sale to consumer is part of this diversity of practices. Also, in developing and transition economies more particularly, much of the economic activity pertains to the informal sector, hence partly hidden, though underpinning very concrete networks in action. Therefore, information is poorly accessible by formal surveys gathering accountancy data with quantitative goals, as performed in classical VC analysis, and actors may not be easily identified and mobilized for actions. Second, the goal is here to derive a thorough understanding of behaviors, motives, and strategies that are relevant to both food chains and health risk management, in order to envision systems' evolution and the conditions for positive change. Therefore, qualitative information on behaviors and motives are paramount, again calling for a step away from classical VC analysis.

Finally, participatory approaches brought the flexibility to combine the structural aspect of VC analysis with behavioral information, given the diversity of bonds between actors, the variety of agents' types, as well as the diversity of motives and risks.

VCs AND BEHAVIORAL ANALYSIS: METHOD AND HIGHLIGHTS

In the continuity of the sustained effort for HPAI control in South-East Asia, participatory VC approaches were used as innovative tools to analyze constraints to HPAI surveillance (32, 33). These studies focus on concepts of incentives and governance, inside a flexible, participatory approach along the poultry VCs, to understand the information flow about animal mortality cases in Vietnam and Thailand. Methods used are mapping of stakeholders, describing actors and relationships between them and further investigations through in-depth qualitative interviews, social network analysis and stated preference methods. These approaches, qualitative in nature, are complementary to another thread of research in the field, rather quantitative, that also mobilizes VCs to understand and prevent HPAI risk in Vietnam from the starting point of markets (34). Joining such systematic and quantitative market characterizations to a wider and more in-depth analysis of VC appears as the backbone structuring the present approach in the context of the prevention of emerging pandemic threats and in the emergency control of HPAI in different countries. Other quantitative modeling approaches applied to VC analysis present potential to contribute to OH-oriented VC analyses, such as system dynamic modeling (35–37). These indeed fit in the here-proposed framework of complexity, taking into account feedback loops, and may implement participatory approaches in building of the models (37). Presently focusing on economic output, sometimes based on health management choices (36), dynamic modeling may account for diverse risky practices and be bound to epidemiological models to generate health-related outputs and perform in-depth risk analysis.

Livestock VC analysis for health risks management may be framed around three main themes: impact, surveillance, and biosecurity (**Figure 1**). To illustrate the approach, practical aspects, and behavioral highlights of VC analysis for health risk management are described here.

Regarding impact analysis, VCs are taken in their primary role of understanding value generation and distribution among stakeholders, considering their diversity and numbers at each level. In current applications, impacts on jobs hold a particular importance in the political agenda for HPAI management in Maghreb, hence influencing public strategies under planning. Within a behavioral perspective, impact analysis presents two main contributions. First, health crisis management results in structural effects on VCs, as in Vietnam where HPAI and its public management reinforced the large intensive poultry production, against the interests of smallholders (38, 39). Modifying power and competition relationships, these structural effects lead to feedback loops between the VC structure and the health risk. Second, actors' anticipations of these impacts drive their decision-making, influencing the risk itself and its impact, e.g., poultry producers anticipate impacts of epizootics on prices and then develop speculative strategies intending to engage in contra-cyclical stocking and selling (33). These anticipations are imperfectly informed and subject to perceptual bias. However, since our interest lies in actors' behavior, relevant data to gather indeed consist in perceptions rather than factual impacts only. Other examples of anticipations by VC stakeholders may concern control measures, market, and farm-gate prices due to mortality, panic, or bargaining effects (33, 40). How impacts are anticipated and affect decision-making is thus crucial in understanding VCs' reaction facing disease risks.

The latter elements are illustrative of the strategic role of epidemiological information inside VCs. Indeed, while public and animal health surveillance may be considered as public goods, even global public goods, these may be rather managed as private or collective ones by VCs actors. Considering the continuum between data, information, intelligence, and knowledge, we observe that information in VCs is often used as strategic intelligence for private use, thus influencing behavior. Within VC analysis, the value produced by each actor and the weight of these actors at each VC level is indicative of stakes in this strategic intelligence, thus incentives to gather disease information and hide or disclose it to targeted business partners. Also, the scale of operation of an actor will determine the geographic area covered by such a private surveillance, defining the so-called epidemiological territories of

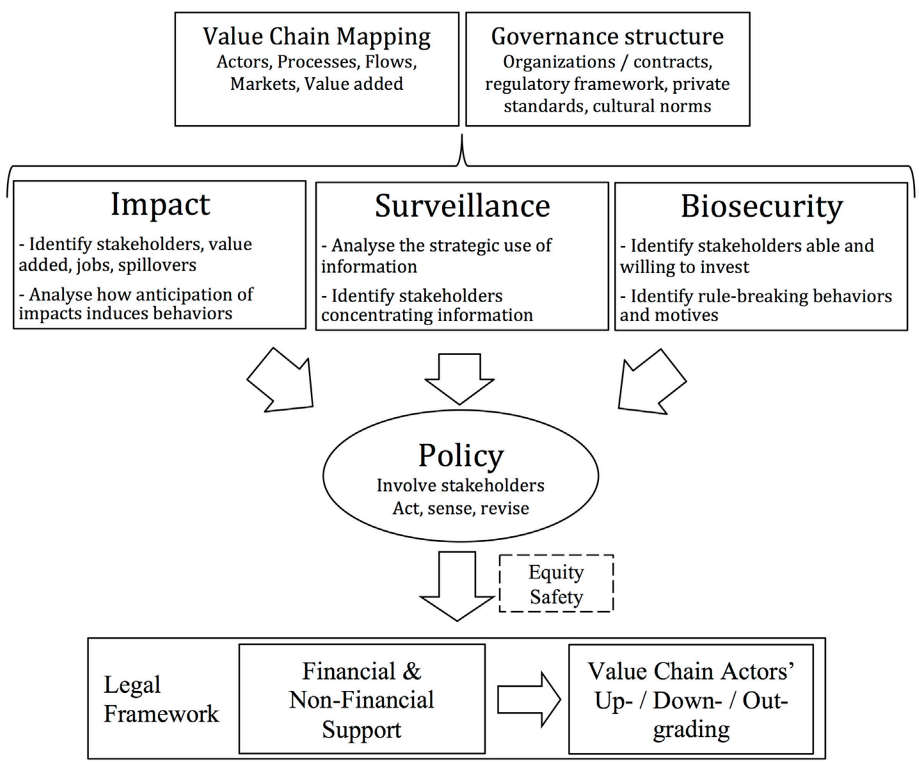

FIGURE 1 | Main threads in value chain analysis and upgrading for health management purposes.

VC actors (41). This scale of operation and concentration at one level of VC will also inform about actors' relative power and ability to influence others' decision-making. Mutual behavioral influence will typically result from vertical integration along the VC, i.e., contracts or ownership bonds between different VC levels, or other commercial links, e.g., credit/debt and persistent network relationships. In the prospect of a participatory management of health risks, these important players identified through VC analysis will be considered as main partners or on the contrary main offenders in the joint management of health information as a public good. Whatever the situation, a first step is to understand the strategic positioning of each actor. Hence, understanding how VC governance affects health information use and epidemiological intelligence should be central to any VC analysis for health management.

The third framing theme is biosecurity, considered in a wide understanding, as being all actions that may be undertaken individually or collectively to prevent the risk studied. A main objective of VC analysis in this respect is to identify the stakeholders able and willing to invest and presenting objective interests in adopting or leading the needed changes. Both aspects relate to the value produced at the actor's level and its access to financial services (insurance and credit), which are central to VC analysis and possible public action to support VC. Again, governance is here crucial due to the externalities of biosecurity measures and the classical coordination problems in managing commons (42). Indeed, besides a vision centered on formal VC actors being partners of its improvement, biosecurity along VC crucially depends on the development of informal and rule-breaking practices. Such practices may result from a lack of access of those actors to the formal VC, due to financial, regulatory, organizational, technological, or even cultural barriers. In a wider understanding, these may be typical free-rider behaviors, motivated by private benefits of not respecting standards and regulations in a context of weak rules enforcement. A difficult but needed judgment to be conducted by regulatory bodies is to understand which actors have to be included in the reinforced VC and which should be controlled to protect other VC actors from their detrimental behaviors. Hence, understanding behaviors and attitudes of VC stakeholders toward biosecurity and identifying incentives or barriers to adhere to biosecurity is crucial for adapting control measures and is part of the participatory analysis of VC.

OPPORTUNITIES, LIMITS, AND CHALLENGES OF VC ANALYSIS

The overall understanding of health challenges within social–ecological systems should benefit from wider and deeper VC analysis. Fundamentally, VC represents a fruitful conceptual framework to analyze actors' behavior and strategies at different levels of the complex systems under consideration. It helps framing complex health problems, guiding action during investigation and triggering change. Although methods envisioned are making several steps away from classical VC analysis to adapt to health complexity, methodological challenges remain, being under constant revision throughout their current application. As detailed below, these challenges come down to a question of framing or setting the problem's boundary, in terms of diversity of actors and processes (including VC supporters and influencers, related VCs), in terms of scales (local, regional, or international markets), or in terms of dynamic (single capture vs. follow-up). The aforementioned question of application of VC analysis to bushmeat and wildlife-related zoonoses is also a topic of current methodological challenges.

The frameworks, as here proposed and presently implemented, present a weakness in not fully taking environmental aspects into account. The SFVC approach and the Life Cycle Analysis methods (43) might be built upon to develop a consistent integrated approach. A more intrinsic limit of VC approach is its focus on a single product and the inclusion of actors in their sole link to this product, with little interest to study inter VC interactions, VC impact on ecosystems, or impact of all VC on inclusive local development. This is particularly constraining in developing countries, where livestock have multiple contributions to livelihoods with known implications in health and environmental questions (44). Also, livestock-keeping households are mostly running multiple activities, as a risk management strategy. Due to this function as well as to epidemiological consequence for cross-species pathogen transmission or joint risk production, this importance of diversification is not to overlook. An additional limit of VC analysis, also particularly constraining in rapidly changing contexts of developing and transition countries, is that it provides a relatively static image of the meso-system studied. Again, a methodological renewal, based on rapid assessment approaches and targeted continuous data collection could help overcoming this issue. However, while tackling all these limits inside the VC framework might appear as interesting methodological challenges, a more direct consequence is the need to keep an awareness of these and more directly overcome them where deemed important by joining other disciplines and frameworks in a behavioral analysis.

CONCLUSION

This article presents how VC analysis contributes to behavioral understanding and change in OH issues. It defends the value of participatory and qualitative approaches, which in turn present an important limit to standardized, multiple countries projects as presently developed for the management of zoonoses and emerging pandemic threats. Obviously, this scaling-up question will remain a matter of trade-off between extensiveness and depth of investigation, as basically taught in social sciences classes. While the needed participatory process is flexible and qualitative in nature, therefore weakly standardized, the joint use of more systematic and quantitative approaches, as markets and flows characterization, risk analysis and system dynamics, is an important answer to generate consistent data to guide decision-making at the national and international levels. This, finally, is not to overlook the basic philosophy of participatory approaches that lies in the fostering of bottom-up changes. Finally, tackling complexity will remain a matter of trade-offs, flexibility, and multiple perspectives.

AUTHOR CONTRIBUTIONS

NA-M: joint experience analysis, writing: drafting, inputs coordination, and finalization. MP: joint experience analysis as CIRAD project leader, and cowriting. PB: joint experience analysis as CIRAD project leader and cowriting. CB: joint experience analysis as FAO-ECTAD West and Central Africa project leader and cowriting. MB: joint experience analysis as FAO-Maghreb project leader and cowriting. AT: joint experience analysis as FAO Animal Health Service officer and co-writing.

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Drivers of Live Cattle Price in the Livestock Trading System of Central Cameroon

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Livestock production and trade are critical for the food security and welfare of rural households in sub-Saharan Africa. In Cameroon, animal trade consists mainly of live cattle commercialized through livestock markets. Identifying the factors contributing to cattle price formation is critical for designing effective policies for sustainable production and for increasing food availability. In this study, we evaluated the influence of a range of individual- and market-level factors on the price of cattle that were sold in all transactions ($n = 118{,}017$) recorded over a 12-month period from 31 livestock markets in the main cattle production area of the country. An information-theoretic approach using a generalized additive mixed-effect model was implemented to select the best explanatory model as well as evaluate the robustness of the identified drivers and the predictive ability of the model. The age and gender of the cattle traded were consistently found to be important drivers of the price ($p < 0.01$). Also, strong, but complex, relationships were found between cattle prices and both local human and bovine population densities. Finally, the model highlighted a positive association between the number of incoming trading connections of a livestock market and the price of the traded live cattle ($p < 0.01$). Although our analysis did not account for factors informing on specific phenotypic traits nor breed characteristics of cattle traded, nearly 50% of the observed variation in live cattle prices was explained by the final model. Ultimately, our model gives a large scale overview of drivers of cattle price formation in Cameroon and to our knowledge is the first study of this scale in Central Africa. Our findings represent an important milestone in designing efficient and sustainable animal health management programme in Cameroon and ensure livelihood sustainability for rural households.

Keywords: cattle, price formation, Cameroon, markets, trading system

1. INTRODUCTION

In Cameroon, the livestock sector contributes 20% of the agricultural gross domestic product (GDP), with trade of live animals and livestock products representing a major component of the agricultural sector (1). As in most of sub-Saharan Africa (SSA), livestock production is particularly important for rural populations, providing year-round employment opportunities and a key source of revenues (2, 3). Notably, the sale of livestock, mainly cattle, is a rapid cash generating mechanism (4) that allows purchasing food and family necessities (3, 5) as well as representing a source of self-insurance against income shocks caused by unforeseen events impacting rural households (5). Livestock, and its associated economic value, represents a key asset for reducing the vulnerability of rural households to a number of external factors, such as climate change, diseases, and social and political instability. However, the strategies available to these households for reducing the severity of animal health and welfare issues on livestock value are generally weak and inadequate (5).

Various studies have been carried out in Cameroon to evaluate the burden of livestock and zoonotic diseases (6–12), identify constraints for disease controls in pastoral and small-scale livestock husbandry and production system (13), and better understand how the cattle trade is structured (14). Together, these studies provide a collection of information which would enable the veterinary services to better design animal health management programmes in Cameroon. However, should these programmes be implemented in the field, their sustainability and efficiency would depend on their degree of integration within the local livestock production system, notably by ensuring a minimum socio-economic impact while guaranteeing benefits for both national and household economies. Developing integrated animal health management programmes, therefore, requires a better understanding of the place (and the perceived value) of livestock in the local economy against which the acceptability and feasibility of intervention would be measured (15).

In this context, a better understanding of the value of livestock represents an important stepping stone in developing efficient and robust, evidence-based animal health interventions. Indeed, knowledge of livestock value represents a key component of any efforts to estimate the economic burdens of infectious diseases (16) and assess the economic benefits of alternative prevention and control strategies (17). However, most economic assessments of animal health strategies assumed livestock farmers sell a homogeneous product with a fixed and constant value. While this assumption may not affect estimated net gain of tested strategies in settings where the price variability is limited, problems may arise in situations where variations in trade behavior vary in time and/or space. In particular, trade behavior may vary in response to environmental and ecological factors, such as droughts and pasture availability, and to shifts in export and meat demand (18), including those related to religious festivities and national celebrations (19). These variations could directly affect the value of livestock and, as a consequence, increase (potentially drastically) the complexity in the socio-economic impact of veterinary intervention strategies on national and household economies and ultimately undermine the success of implemented animal health programmes.

The lack of a reliable price information system is a common constraint when attempting to improve our understanding of livestock marketing systems in both the pastoral production and urban consumption areas across most of SSA (20, 21). In Cameroon, livestock trade is predominantly represented by sales of cattle in conventional trading infrastructures (1, 14) regulated by the Municipalities and by the local Delegations of the Ministry of Livestock, Fisheries and Animal Industries (MINEPIA). In markets located in the Adamawa and West Regions of Cameroon, two of the main cattle production areas of the country, details on prices, provenance and characteristics of each animal traded are recorded (in various forms) and kept locally mainly for tax collection purposes. Once collected and centralized in a unique dataset, these records represent a unique resource for better understanding the factors that drive formation of live cattle price in Cameroonian trade system. In the current study, the aim was to use this collection of market records to evaluate which animal and market factors contribute to cattle price formation and estimate how these factors influence live cattle prices within the livestock trading system of the major livestock production areas of Cameroon. Specifically, we developed a generalized additive mixed-effect model and applied an information-theoretic approach derived from the ecology literature (22) to identify factors (as well as evaluating their robustness) impacting on the value of traded cattle in Cameroonian markets.

2. MATERIALS AND METHODS

2.1. Study Population

In this study, all markets that are involved in the trade of cattle and are located in the West, North-West, and Adamawa Regions of Cameroon were considered for inclusion. These include all markets listed in the livestock market registers from the relevant Regional Delegation of the MINEPIA of the West, North-West, and Adamawa Regions of Cameroon ($n = 52$) as well as additional markets ($n = 7$) identified through interviews with veterinary officials and market managers (14).

From the 59 markets considered in this study, all data related to cattle transactions reported in official market records were obtained for a 12-month period from September 2013 to August 2014. In Cameroon, details of cattle transactions in markets are recorded on paper and handwritten. Market records were therefore scanned using a portable wireless scanner and a smartphone, manually transcribed to an electronic database by two persons separately and cross-checked for discrepancies. When erroneous or missing records were identified, original scans were re-examined and data re-entered in the database. Semi-structured interviews were also conducted with the veterinary officials and market managers using French and English (Cameroonian official languages) to gather additional background information regarding the transaction process and the roles of the different stakeholders involved in the negotiations.

Among all markets considered in this study, only 31 cattle markets (53%) recorded detailed information for each individual transaction occurring within the study period. In total, 118,017 cattle transaction records were extracted from the archives of these 31 markets. **Figure 1** shows the study area as well as the location of the 31 markets involved in the current study.

Briefly, the study area covers the Adamawa and The West ("Ouest") Region of Cameroon (**Figure 1**). The Adamawa Region is mainly a pastoral highland above 1,000 m, of approximately 64,000 km^2 and considered to be the main livestock production area of Cameroon with an official cattle population of about

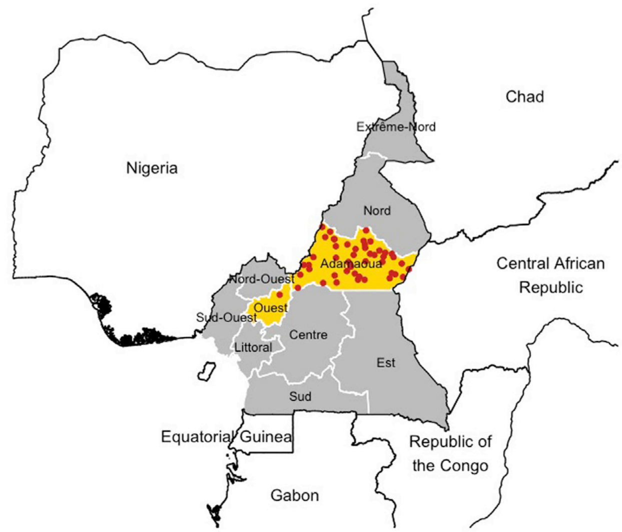

FIGURE 1 | Study area and locations of the livestock markets included in the analysis. The Regions in yellow highlight the areas where data collection was carried out and the red dots refer to the locations of the markets.

1,250,000 head of cattle (23) and an open woodland Guinea savannah ecotype. It is both a source and a destination of transhumant herds originating from other areas of the country during the dry season (October to April). The West Region is a lower lying area of 14,000 km^2 with a much smaller cattle population of about 160,000 heads (23) and a more Sahel woodland savannah ecotype. Together, both Regions contain about a quarter of the national cattle herd.

2.2. Predictor Variables

The extracted 118,017 records of cattle transaction considered in this study included not only the price (in Central African Franc, CFA) at which individual animals have been traded but also the date (in week) and location (market name and administrative Division) of the transaction. To account for potential seasonal variations in the price of live cattle, transactions were determined to have occurred during either the dry or the rainy season. For the purpose of this study, the dry season was considered to be occurring between October and April, and the rainy season between May and September. For each transaction, details of several individual-level characteristics of the traded animal were also reported, including the village or the market of provenance of the animal, its age and its sex. All cattle traded were also recorded as belonging to one of the following specific commodity types: "steer," "bull," "cow," "young bull," or "heifer."

Over the entire dataset, information on price, commodity types, date, and location were complete for each recorded transaction. However, nearly 20% of the official records showed missing information on the age of the animal traded. To avoid loss of information, missing information on cattle age was imputed using a matching imputation approach (24). Briefly, we assumed that missing information was missing completely at random and represented a random subset of the data. As such, age information was imputed by matching known details of the animals for which age is missing with those of animals for which age was reported. Here, we matched animals based on their specific commodity type (i.e., steer, bull, cow, young bull, or heifer), the market at which they were sold and the month of the transaction. Figure S1 in Supplementary Material compares the age distribution from the incomplete dataset with that from the dataset including the imputed observations. Although the general age distribution remains consistent, there were some clear errors when inferring the exact individual age. Particularly, 3- and 4-year old animals were difficult to discriminate, while age of >10 years old animals were difficult to estimate with certainty. To avoid biases, cattle were therefore regrouped into five age categories levels with similar age intervals: ≤2 years old, between 3 and 4 years old, between 5 and 6 years old, between 7 and 10 years old, and >10 years old.

Details of markets in which transactions occurred were also included in the data. The total number of transactions that occurred in each market was used as a proxy for their size and, thus, their importance in the trade system in Cameroon. However, the precision of such a measure is limited as it does not consider the global structure of the trade system and disregard markets potential to access others. To capture this feature, we considered cattle markets in Cameroon to form a large network, where markets are "nodes" of the network that are directly linked by the movement of cattle that were purchased and/or sold. The formal analysis of the cattle trade network in Cameroon has been previously published in Ref. (14), including the study of several network centrality measures (including degree, in- and out-degree, betweenness, and eigenvector) computed to extract the position of markets in the trade network and identify which markets are more "central" than others. Detailed definitions of the considered centrality measures and their characteristics are provided in Ref. (14). However, in the present analysis, only in-degree was considered as an indicator of network position for markets. This is because (i) centrality measures are highly correlated (25), particularly in regard to the cattle trade network in Cameroon (Table S1 in Supplementary Material); (ii) the estimate of in-degree can be easily and reliably calculated from transaction records in Cameroon; and (iii) the estimate of in-degree is relative stable, even in situation where incomplete network information occurs (26).

We further recorded the geographical location of each cattle market using a Global Positioning System (GPS) at the time of the data collection. From the obtained latitude and longitude of markets, estimates of human and cattle population densities were extracted from raster datasets freely available online (27, 28) to account for the distribution of populations and their potential impact on the local demand and supply capacity for cattle meat. We assumed that the individual demand for cattle meat is directly related to local human density, whereas supply would be affected by the local density of cattle. For the purpose of analysis, we further assumed that both cattle and human populations were stable overtime and could be extrapolated from historical, though recent, information. Data on cattle population density were extracted for the year 2005 from the Gridded Livestock of the World (GLW) version 2.0 (29), freely available at the FAO

GeoNetwork repository (27). Information on the human population density the year 2010 was obtained from the WORLDPOP data (28).

2.3. Statistical Analysis

2.3.1. Modeling Framework

A generalized additive mixed-effect modeling approach (GAMM) (30) was used to estimate the effect of animal- and market-level factors influencing the value of cattle in the study area during the period September 2013 to August 2014. For this analysis, the outcome was the price (in thousand CFA), Y_{ij}, of animal *i* at market *j*. Here, the price Y_{ij} was assumed to be linearly dependent on a set of *k* predictor variables x_k and on *m* unknown smoothing functions f_m of non-linear predictor variables z_m such that:

$$g(E(Y_{ij})) = \alpha + \sum_k \beta_k x_{ki} + \sum_m f_m(z_{mi}) + U_j + \epsilon_{ij} \quad (1)$$

where $g(E(Y_{ij}))$ is the linear link function of the expectation of the price $E(Y_{ij})$; α is the intercept; β_k are the coefficients of the assumed independent predictors x_k; and ϵ_{ij} is the error term or "residuals." A random effect term U_j was added to account for correlation arising from repeated information from the same market.

Animal and market-level characteristics of each transaction were considered as predictor variables in the model. To comply with the underlying assumption of independence, relationship between predictor variables was visually screened, and their correlation was evaluated by computing the Pearson's correlation coefficient *r*. Variables showing $r > 0.6$ were identified and only the biologically or economically most relevant variables were considered for the modeling. In particular, market size, as defined by the number of traded cattle over a 12-month period, was highly correlated with in-degree centrality ($r = 0.62$) and was therefore discarded from further analysis.

Finally, preliminary analyses highlighted the non-linear relationship of the cattle price with both the local bovine population density and the week of the transaction (see Figures S2 and S3 in Supplementary Material). As such, both variables were included in our model as non-linear predictor variables z_m and were modeled using penalized regression splines. Details for the nine independent variables that were considered as potential drivers of cattle value in markets and use in the analysis are given in **Table 1**.

The modeling was conducted using the *gamm4* package (31) in R statistical software version 3.2.3 (32). The mapping was generated using R statistical software (32) (version 3.2.3) using the *raster*, *rgdal*, and *ggplot2* packages and shp files obtained from the GADM database of Global Administrative Areas version 2.0 (www.gadm.org).

2.3.2. Model Selection and Validation

The size of the dataset offered the opportunity to assess the variability of the model fit and to increase the confidence of its robustness and its predictive performance. As such, the dataset was split into two subsets: a testing set and a validation set (33). The former was used to model the data and select the final model, whereas the latter enabled us to evaluate the predictive performance of the model. For the purpose of this study, the validation set was composed of 10% of the entire data ($n = 11{,}800$) using a stratified random sampling method. This sampling method was used to ensure that a representative fraction for each commodity type was present.

Model selection was carried out using the information-theoretic approach (34). This approach is derived from ecological theory and consists of fitting various combinations of the putative drivers together for multiple sampled subset of the data to derive the final model from the set of possible candidates. In this study, 50 bootstrapped samples of equal size ($n = 11{,}800$) were randomly generated using a stratified approach from the testing dataset (i.e., resampling the data with replacement). For all 50 subsets, 24 candidate models were considered and compared to identify the final model (Table S2 in Supplementary Material). As recommended by Ref. (34), fitting performance was evaluated based on the Akaike Information Criterion (AIC (35)) and the adjusted coefficient of determination (R^2) (33, 36). The AIC provides evidence for which combination of variables best explained the data with the minimal number of covariates, whereas the

TABLE 1 | Variables used to build the modeling approach of cattle price at the market level.

Name	Variable	Data type	Definition
AGE	Age	Ordinal	A categorized variable with five levels (<2, 3–4, 5–6, 7–10, >10 years old)
SEX	Sex	Binary	Male or female
SEAS	Season	Binary	Season at which transaction occurred: dry (October to April) or rainy (May to September)
DIV	Division	Categorical	Names of the six Divisions: Djerem, Faro et Deo, Mayo Banyo, Mbere, Vina and Noun)
CD	Cattle density	Continuous	Density of cattle living in the administrative area of the market as extracted by the online repository varied between 0 and 30 animals per km^2
HD	Human density	Ordinal	Density of human living in the administrative area of the market as extracted by the online repository was categorized in three levels (low: 1–50, medium: 50–200, and high: >500 per km^2)
IDEG	In-degree	Continuous	In-degree centrality of the market in the cattle trade network in Cameroon (ranging from 0 to 16 incoming trade connections per market or, in other words, of unique source markets of animals moving in each specific market)
MKT	Market	Categorical	The ID of the 31 livestock markets (M1 to M31) where the report data were obtained
WEEK	Week	Ordinal	The week of the year that the report was made as an ordinal variable (from the September 1, 2013, to the August 31, 2014)

adjusted R^2 statistic provides a more "global" measure of how good the model is at explaining the data by measuring the amount of variance explained by the model. It worth noting that both AIC and adjusted R^2 are measures that penalize for the number of independent variables in the model. As such, these statistics provide measures of support for the most parsimonious model. For comparison, the ΔAIC was also extracted for each tested model by computing the difference between each model-specific AIC and the highest AIC among all tested models. The proportion of times each candidate model returned the lowest AIC value, ϕ, was also recorded. Calculation of this proportion determines the relative frequency that any candidate model is found to be the best (34).

For each candidate model, statistical significance for both linear and non-linear variables was set at $p < 0.01$. The proportion of times each variables were found significant in candidate models, π, was also computed. This proportion π provides a measure of support for each association, which due to the use of bootstrap resampling is robust to the effects of sampling error in the original data.

Predictive performance of the final models was evaluated by comparing model-based predictions with observed prices of cattle from the 11,800 transactions that were included in the validation dataset by using the adjusted R^2 and the mean absolute error (MAE). The MAE measures the selection bias contributing to make the model inaccurate. By determining if the model has a positive or negative bias, it is possible to assess if the model is underestimating or overestimating the observed values (37).

3. RESULTS

Over the entire dataset of transactions, live cattle were sold on average for 222,000 CFA (Q1–Q3 range: 170,000–290,000). Throughout the 52 weeks of the study period, the average price of cattle varied by ±4.5%, with a minimum during weeks of the dry season and a peak during the week before end-of-year festivities (Figure S3 in Supplementary Material). However, there was large variation in value between commodity types (i.e., bulls, steers, cows, young bulls, and heifers), with bulls and steers traded for the highest median price at 325,000 CFA (Q1–Q3 range: 291,000–390,000) and 338,000 CFA (Q1–Q3 range: 270,000–402,000), respectively (**Table 2**). In contrast, young stock (i.e., heifer and young bulls) were sold with a 23% discount in comparison with the average cattle price, at a median price of 170,000 CFA (Q1–Q3 range: 140,000–215,000).

In total, 24 models were screened to identify factors affecting the price at which cattle were sold in Cameroonian markets. Each model included different *a priori* meaningful combinations of the nine predictor variables considered. Figure S2 and Table S2 in Supplementary Material provide the list of all models screened and the formal comparison of their fitting performance, respectively. Models 1 and 5 showed equivalent fitting performance with an adjusted R^2 of 0.474 (range: 0.423–0.501) and 0.474 (range: 0.456–0.403), respectively, while minimizing their estimates of ΔAIC (**Figure 2**). Both models include: the week at which transactions were made; the age and sex of the animals involved in these transactions; the administrative division of the markets; the position (i.e., in-degree) of these markets in the cattle trade network in Cameroon; as well and the local densities of human and cattle reported at their location. Although Model 1 showed the lowest AIC in 82% of iterations, the additional factor included in this model, season, was not statistically significantly associated in any of the 50 iterations ($\pi = 0\%$). Given that AIC and R^2 measures from Models 1 and 5 were not significantly different (**Figure 2**), we considered Model 5 as the best, most parsimonious, model.

Regression coefficients and their standard errors for all linear variables (i.e., the age and sex of the animals, the administrative division of the markets, in-degree, and human density) included in the final model are shown in **Table 3**, whereas the shapes of the functional forms for the non-linear variables (i.e., the week of the transaction, and bovine density) are shown in **Figure 3**. Although the temporal variations in the model is consistent with the empirical observations (**Figure 3A**), with the lowest price occurring during the dry season and a small peak prior the festive season, the week at which transactions were made had little influence on the mean price of live cattle ($\pi = 0\%$). On the other hand, both animal

TABLE 2 | Descriptive statistics of live cattle prices recorded in markets of the Adawama and the West Regions in Cameroon.

	Bull	Cow	Steer	Heifer	Young bull	All categories
n	29,819	36,854	2,097	16,872	32,375	118,017
Overall	325 (291–390)	220 (193–250)	338 (270–402)	170 (140–201)	171 (140–215)	222 (170–290)
Division						
Vina	348 (307–400)	235 (200–270)	305 (260–374)	182 (150–220)	191 (155–230)	220 (175–290)
Djerem	306 (245–360)	200 (170–230)	320 (270–361)	146 (120–175)	162 (130–200)	185 (145–250)
Faro et Deo	301 (240–365)	169 (130–205)	302 (240–350)	132 (105–165)	128 (100–162)	150 (115–210)
Mayo Banyo	305 (271–338)	215 (192–248)	274 (218–320)	158 (142–182)	161 (147–175)	215 (179–285)
Mbere	342 (300–402)	208 (177–252)	363 (290–400)	162 (130–200)	181 (143–232)	220 (165–305)
Noun	338 (287–405)	232 (205–275)	396 (344–462)	180 (147–215)	175 (145–210)	250 (200–317)
Season						
Dry	328 (288–390)	220 (190–252)	344 (260–400)	172 (145–210)	175 (140–220)	226 (170–290)
Rainy	322 (300–390)	218 (200–245)	335 (275–400)	166 (142–214)	170 (140–200)	220 (160–290)

n: total number of transactions reporting sale of live cattle.
All values are median (interquartile range) of the price (in ×1,000 CFA) at which individual live cattle have been sold in markets of the study area and stratified by administrative Divisions and season.
Noun is a Division of the West Region, whereas all others are Divisions of the Adamawa Region.

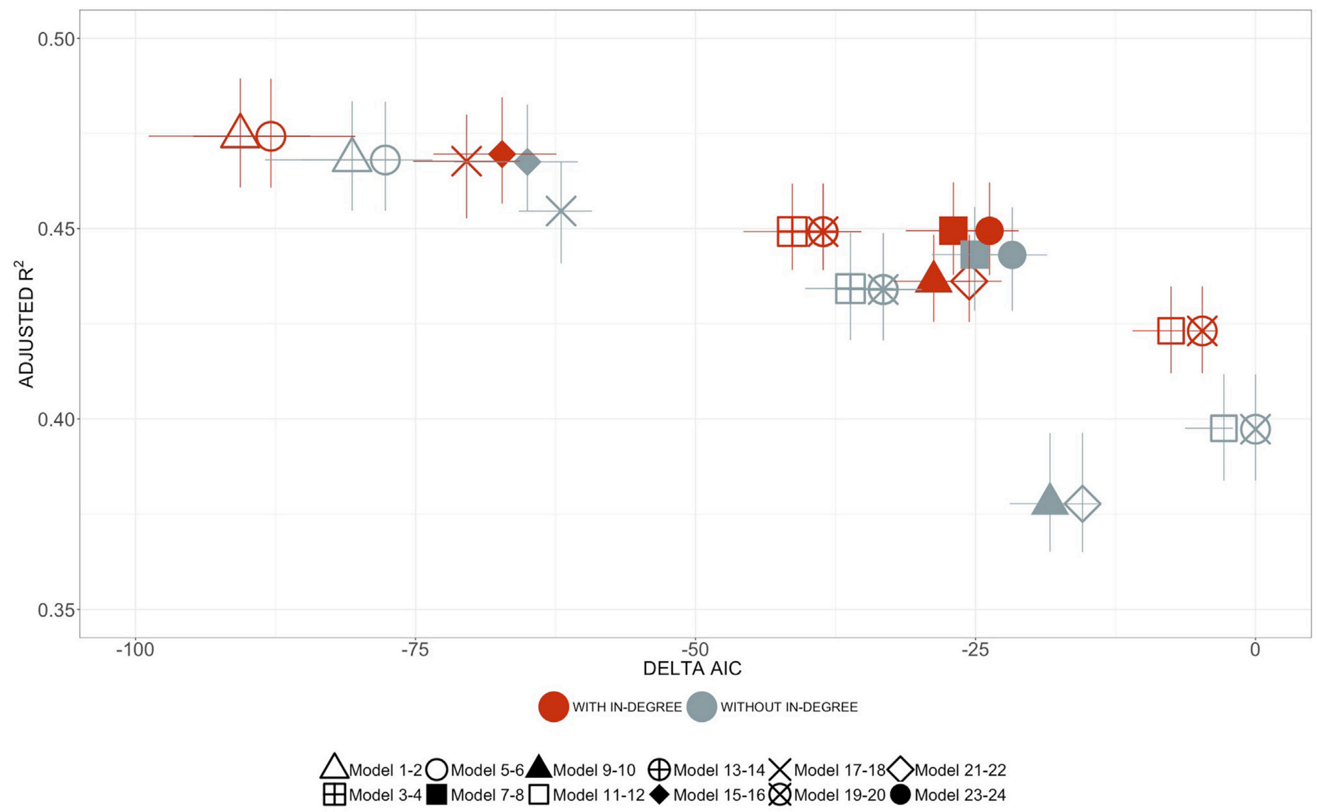

FIGURE 2 | Effect of market centrality on models performance. The mean values of ΔAIC are displayed on the *x*-axis. The mean values of the adjusted R^2 for each model, with the bars representing the ranges of variation across the 50 iterations, are displayed on the *y*-axis. The structure of each model is shown in Table S2 in Supplementary Material. The red color refers to models with in-degree centrality as a predictor, whereas gray color refers to models without in-degree. The shapes of the points refer to equivalent models, only differing by the inclusion or exclusion of in-degree centrality among the predictors. For example, the red square shape is equivalent to the gray square shape. The models are formally described in the Supplementary Material (Table S2 in Supplementary Material).

age and sex were consistently associated with the value at point of trade, showing a $p < 0.01$ in all iterations of the model (**Table 3**). On average, individuals between 5 and 6 years of age consistently attained the highest price, amounting to 127,000 CFA more [95% confidence interval (CI): 123,668–130,332] than 0–2-year-old animals. However, cattle in Cameroon still retain significant value despite aging, with >10 year-old individuals worth on average 104,000 CFA more (95% CI: 98,296–109,704) than 0–2 year-old animals. Males on average attained a significantly higher price than females, with males (bulls and steers) 68,500 CFA (95% CI: 66,089–70,911) more expensive than females (cows and heifers).

The position of the market in the cattle trading system was consistently associated with price of traded cattle, showing a $p < 0.01$ in at least $\pi = 96\%$ of the iterations (**Table 3**). On average, the price of cattle would increase by 2,800 CFA (95% C.I.: 1,291–4,309) with each unit increase of in-degree centrality, corresponding to a unique source market. Although such an increase may seem minimal, in-degree was influential across all the models screened during the selection process, consistently showing better R^2 and ΔAIC values than models where in-degree was dropped (**Figure 2**).

The trade price of cattle in markets was consistently associated with both the density of cattle ($\pi = 96\%$) and the density of human populations ($\pi = 64\%$) in the area where markets are located. Indeed, cattle prices were significantly higher in markets where the local human population density was low, with an additional 20,900 CFA (95% CI: 6,376–35,424) in the value of cattle compared to markets located in areas with medium human density (**Table 3**). At the same time, cattle were consistently 50,000 CFA cheaper in markets where cattle were at a low density (i.e., <13 per km^2) and their value progressively increased with an increasing local cattle density until it reached a maximum price around 23 cattle per km^2 (**Figure 3B**).

Despite adjusting for local conditions, a relevant variability in the price of cattle still remains across the study area. The price of cattle traded in the Djerem and Mayo Banyo Divisions of the Adamawa Region were consistently cheaper than the rest of the Divisions in our analysis ($\pi = 100\%$, **Table 3**). On average, cattle traded in markets located in Djerem and Mayo Banyo Divisions were sold for 34,500 CFA (95% CI: 21,133–47,867) and 31,500 CFA (95% CI: 19,348–43,652) less than cattle sold in the Vina Division (Adawama), respectively. However, prices did not differ only between Divisions, live cattle were traded for significantly ($\pi \geq 96\%$) less than expected in four markets (Nyambaka, Likok, Mbe, and Banyo) whereas prices were inflated in three markets (Dibi, Djalingo, and Ngaoui) (Figure S4 in Supplementary

TABLE 3 | Mean estimates, and their associated variability and robustness, from the multivariable generalized additive mixed models of factors influencing the value (×1,000 CFA) of live cattle in markets of the Adawama and West Regions in Cameroon.

	Estimates (95% range)	SE (95% range)	π
Intercept	100.0 (91.4, 109.0)	7.70 (7.65, 7.74)	100%
Age			
0–2	Ref.	–	–
3–4	81.2 (78.1, 85.8)	1.58 (1.58, 1.58)	100%
5–6	127.0 (122.1, 130.4)	1.70 (1.69, 1.71)	100%
7–10	113.2 (108.0, 117.2)	1.97 (1.95, 1.99)	100%
>10	104.3 (98.6, 111.2)	2.91 (2.91, 2.92)	100%
Sex			
Female	Ref.	–	–
Male	68.5 (65.5, 71.4)	1.23 (1.22, 1.23)	100%
Human density			
Low	20.9 (14.2, 28.4)	7.41 (7.36, 7.45)	64%
Medium	Ref.	–	–
High	−6.59 (−17.2, 6.42)	12.3 (12.2, 12.3)	0%
Network in-degree	2.80[a] (2.14, 3.66)	0.77 (0.76, 0.77)	96%
Division			
Vina	Ref.	–	–
Djerem	−34.5 (−40.9, −26.4)	6.82 (6.78, 6.86)	100%
Faro et Deo	4.00 (−3.18, 5.12)	10.34 (10.24, 10.48)	0%
Mayo Banyo	−31.5 (−36.1, −28.1)	6.20 (6.16, 6.24)	100%
Mbere	−11.6 (−17.1, −4.53)	7.69 (7.64, 7.74)	0%
Noun	−5.79 (−17.94, 9.52)	14.41 (14.22, 14.60)	0%
Random effects			
Market	2.4 (−8.4, 10,1)	11.24 (10.63, 11.81)	–

Ref., reference; SE, standard error; π, proportion of significance defined as the number of iterations in which variables are significant (i.e., $p < 0.01$) over the 50 bootstrap iterations.

The variability of the regression coefficients was informed by the mean standard error (SE) whereas their robustness was informed by their 95% range computed over 50 bootstrap iterations. Confidence intervals (CI) for the linear variables can be calculated as the Estimate ± 1.96 × SE.

[a] Interpretation: The price of cattle would, on average, increase by 2,800 CFA (95% C.I. 1,291–4,309) for each unique market sending animals to the specific market in which transaction occurred.

Material). **Figure 4** highlights the spatial distribution of market-level impacts (i.e., random effect) on the price at which cattle were sold once adjusted for all linear and non-linear predictors. Clearly, no particular spatial patterns were apparent. However, it is interesting to note that four of the seven markets for which prices of cattle deviate significantly from the adjusted average are located in the Vina Division (Adawama).

Goodness-of-fit measures for the final model over the testing dataset are shown in **Figure 2** and Table S2 in Supplementary Material. There was some variability in the value of cattle that was not explained in the model, with adjusted R^2-values averaging around 0.474 (range: 0.456, 0.493). However, the quantile–quantile (QQ) plot of both the distribution of the residuals and random effects of the final model did not deviate massively from that expected under the null hypothesis (**Figure 5**). Acknowledging that imputed age data may have influenced the model outcomes, 50 iteration models were fitted over the reduced, non-imputed data. Whether the model used imputed aged data or not, little differences were found between estimates of the explanatory variables and between goodness-of-fit measures, confirming the robustness of the model outcomes.

We assessed the predictive performance of the model by examining how its predictions agree with the recorded cattle prices from the validation dataset. The adjusted R^2 was 0.474 indicating that although a relatively high concordance exist between model inferences and recorded prices, only 47.4% of the variability in the data was accounted for. On average, predictions deviated from recorded prices by about 50,000 CFA (MAE = 49.6), equivalent to 23% of the mean cattle price across the study area. When comparing predictive ability of the model across the different cattle types, the price of bulls and steers was generally underestimated by a median of 26,800 CFA (Q1–Q3 range: −13,200–78,000) and 50,600 CFA (Q1–Q3 range: −14,200–105,200), respectively. Similarly, the price of heifers was underestimated by an average of 25,100 CFA (Q1–Q3 range: −8,000–53,600). In contrast, young bulls were traded, on average, for 32,900 CFA (Q1–Q3 range: 2,100–64,300) less than what we predicted based on our model (**Figure 6**).

4. DISCUSSION

Many epidemiologist and policy makers have argued about the importance of local trading behavior on the efficiency and resilience of animal health management programmes implemented in rural communities. While incentives and compensations have been shown useful to increase the rate of reporting of infectious disease occurrence (38), these may be counter-effective if the compensation offered is too low or affect the sustainability of the programme if it is too high. Evaluating the prices at which livestock owners will be willing to report disease signs, while ensuring the sustainability of the programmes, is therefore critical. Yet, little information can be found in the literature on what affects the value of agricultural products (let alone for livestock commodities) in their local settings in SSA. Instead, research has been focused on the impact of shocks, either due to environmental changes, e.g., drought (18, 39), or fluctuations in global agricultural market prices (40, 41). These are important factors to consider when designing efficient animal health programmes. However, animal health programmes in SSA depend on long-term commitment of local rural communities that are heavily reliant on livestock production. In this context, governments face two key questions when setting prices: (i) what is the minimum price livestock owners would accept in compensation that provides sufficient motivation to report clinical signs and (ii) how variable are prices and how much local adjustment needs to be made in compensation. While the former would ensure the cooperation and willingness of livestock owners to report clinical signs, the latter would avoid undesirable effects on trade that may affect the ability of animal-health officers to predict (and control) diseases spread. Here, we focused on the second question, highlighting for the first time factors that determine the formation of live cattle price at livestock markets within the major pastoral and cattle production areas of central Cameroon.

As expected the value of animals varies between commodity types. Adult males (either bulls or steers) were the most expensive type of animal whereas young stocks (i.e., heifer or young bulls) were the cheapest (**Table 2**). Bulls and steers, are usually

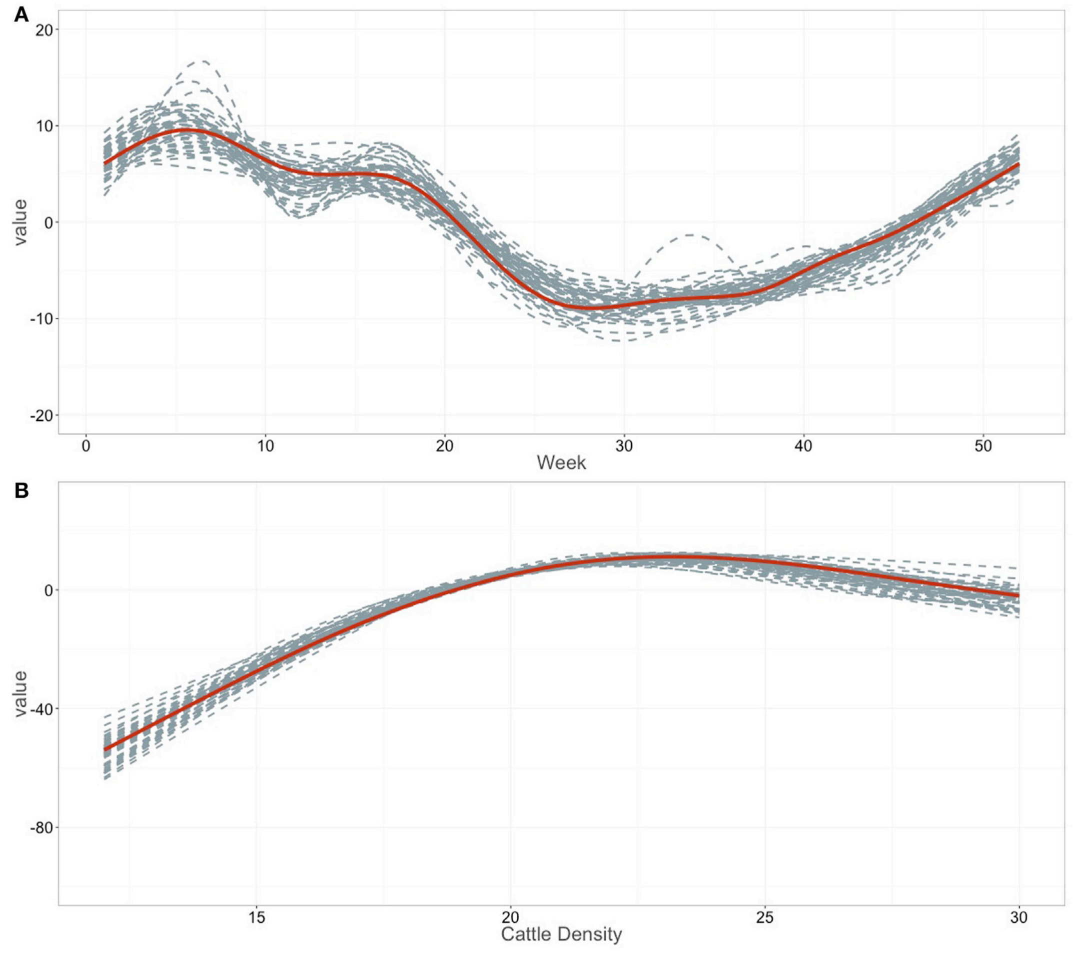

FIGURE 3 | Smoothed fits of covariates. Smoothed fits of covariates modeling the relation with **(A)** the weekly observation and **(B)** the bovine population density. Tick marks on the *x*-axis are observed datapoints, and the *y*-axis represent the spline function. Gray dashed line indicates the smoothed fits for all the 50 iterations; the red solid line the mean smoothed fit across the 50 iterations.

considered the most suitable for human consumption in various contexts (42, 43) and their value can be directly estimated by buyers. In contrast, females are mostly kept for breeding purposes in Cameroon, and their value is more long term, but also more uncertain as they may fail to breed in the future. However, healthy cows are still important assets in the herd and will only be traded for slaughter (usually at lower price) near the end of their reproduction life to recover money (12). It is therefore surprising that so many cows are being offered for sale in the study area. Lower prices were paid for young stock compared to adults, with a median 23% lower compared to the overall median price of live cattle. The low price of young bulls may be explained by either the large number of young bulls being offered for sale in the markets (27%, **Table 2**), or because of their lower weight or the uncertainty in their growth to optimal slaughter weight. On the other hand, heifers are typically kept in their herd of birth as replacements for unproductive cows. However, nearly 14% of the total number of animal traded in the study period were heifers. We can only speculate on the reasons why heifers were traded rather than kept in herds as replacement stock. Heifers could be perceived by herdsmen as a better animal to trade to generating rapid cash to pay bills or unforeseen expenses (4, 44). Alternatively, herdsmen may sell cattle (including heifers) if they suspect that they suffer from a health-related issue [i.e., as an emergency sale (45)]. As such, it is not surprising that the age and sex of the animals involved in transactions were found to be consistently associated with their price in the final predictive model (**Table 3**).

Cattle production in Cameroon depends almost exclusively on the traditional pastoralists who rely entirely on communal pasture land to meet the needs of their animals. Seasonal variations in the production and nutrient content of pastures have been correlated with the poor performance of cattle elsewhere in SSA (46), including Cameroon (47). Although our study only covers a single year of trading records, the period at which prices are minimal, visually coincides with the period during which pasture productivity is low (i.e., the dry season) resulting in poorer animal body conditions. However, temporal changes in cattle prices were minimal, representing less than 5% of the

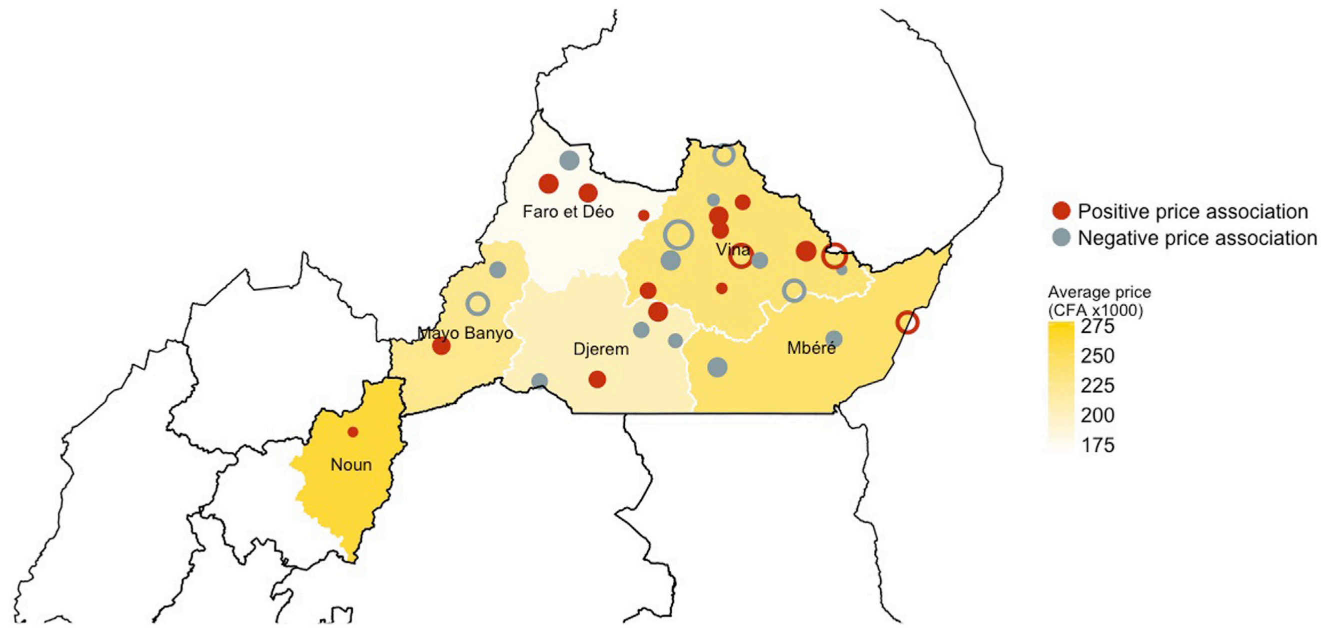

FIGURE 4 | Geographical distribution of the markets and their estimated effect on the price of the traded cattle across the study area. Red color relates to markets with a positive association on price of live cattle, while gray color relates to markets which a negative association on price of live cattle. The size of the dots is proportional to the mean impact on price of the market over the 50 iterations: the bigger the dot the bigger the effect on the price. Open circles refer to the market that have a consistent, either positive or negative, effect on price across the 50 iterations. The intensity of the yellow background color, instead, relates to the mean price of animals traded in each division within the study area.

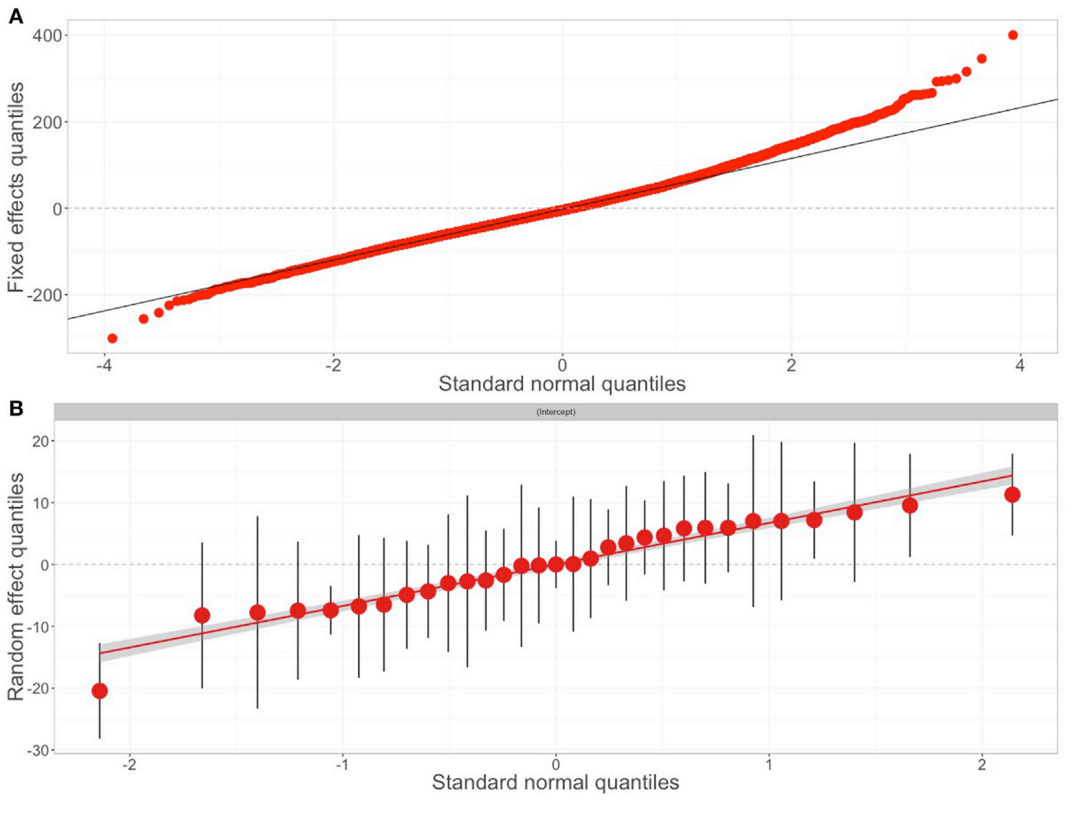

FIGURE 5 | Goodness of fit of the final model. Scatter plots of the goodness of fit for the final model. Quantile–quantile plots of **(A)** the residuals errors and **(B)** random effects (31 markets) of the final model. The plots show a uniform distribution with only an increased deviation from normality for the extreme values.

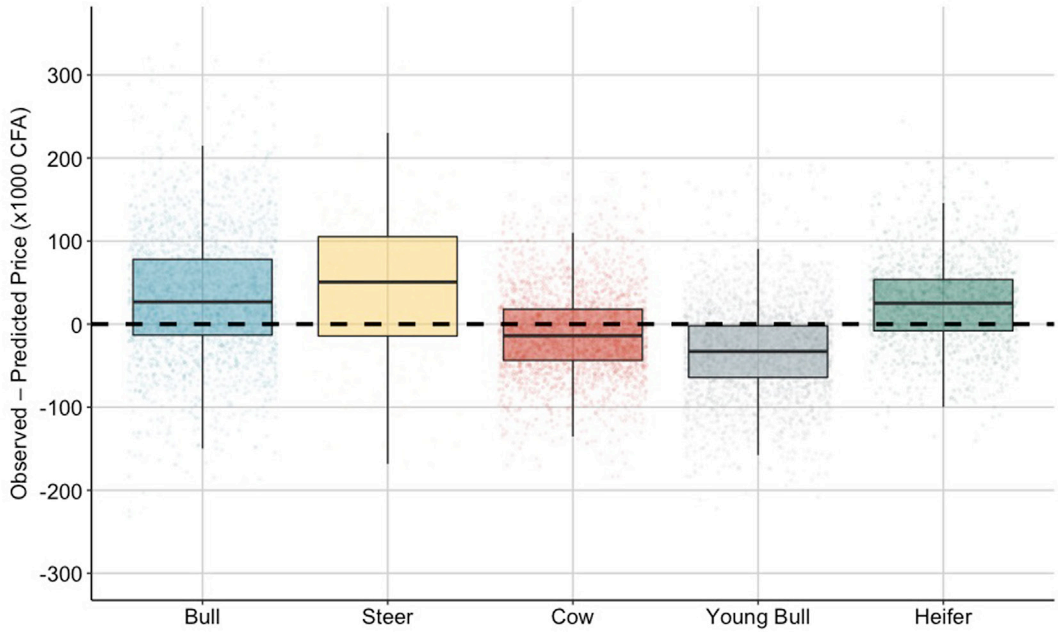

FIGURE 6 | Predictive ability of the model. Boxplot of the difference between the observed and predicted prices (in CFA ×1,000) for each of the categories of traded cattle. For each box, dots represent the differential in prices for each records from the validation dataset. The upper, lower hinges and horizontal lines indicate the 1st and 3rd quartiles (the 25th and 75th percentiles) and the median of the distribution, respectively. Dashed horizontal line indicates perfect prediction.

variation around the average cattle price. Also, we found poor evidence of effects of different periods of the year on live cattle price and no clear relation of higher prices during periods of religious festivities or national celebrations, as previously suggested elsewhere (15, 19). This may be because the study area is predominantly Muslim and sheep are more important in their religious celebrations. Although these results do not imply that external shocks, such as drought for instance, would not be influential in driving the price of cattle in the study area, these findings highlight that live cattle prices are robust to temporal factors and therefore these appear less important for setting compensation values.

The common wisdom in price formation is that supply and demand will regulate the price of commodities that are being traded (15). In the context of cattle prices, we would have expected prices to increase in markets located in areas where the cattle population density is low and the human population density is high. Conversely, markets in areas where the cattle population is high and the human population is low, should have recorded lower cattle prices. However, this relation was not linear in the present study. Our model shows that, on average, a 20,900 CFA and a 50,000 CFA premium were paid for cattle in markets located in low human population density and high cattle density, respectively. While these findings need to be regarded with caution, they should be considered and interpreted in relation to the specific features of the study area. The Adawama and West Regions represent the main cattle production areas in Cameroon, raising nearly a quarter of the national cattle herd (1), while also including a limited number of urban centers (23). It is clear that the large volume of cattle produced cannot be consumed by the local population and part of the production is redirected toward large urban centers outside the study area (such as Douala or Yaounde) or exported. While efforts were made to include markets from high consumption Regions outside the study area, records of market transactions in these Regions were not available and therefore inferences on price formation are only valid in the context of the study area.

Our previous assumption that population density was directly related to the consumption demand for live cattle and cattle meat fails to capture the structural complexity of the trading system in Cameroon. In particular, the network is not homogeneous and different actors operate at different levels in the network. Our results have shown that the average price paid for each animal is affected by the position of markets in the cattle trade network, with a premium of 2,800 CFA paid for each additional unique market from which they source animals (in-degree). Although the reasons why animals would be purchased for greater price in more central markets are not totally clear, it is believed that this might be related to greater demand for live animals for either slaughter or re-sell. At the periphery of the network are large numbers of livestock owners selling into the market to relatively few buyers and very few butchers/dealers. As animals move through the network to more central markets (i.e., with higher in-degree), the profile of actors changes with local dealers selling batches of cattle to a large population of butchers and traders who are trading directly to large urban centers outside the study area.

Previously it has been shown that increasing the number of incoming connections to nodes of a network, in our case markets, could promote the circulation of pathogens, particularly rapidly spreading infectious diseases (48–50). As such, targeting key markets as part of surveillance strategies has the potential to increase the disease detection sensitivity of the surveillance system. Several studies have been carried out in SSA to investigate the structure and dynamics of livestock trade networks (14, 49, 51). However, these networks are difficult to compile, usually through carrying out questionnaire interviews to traders and livestock owners and may suffer multiple methodological limitations that may bias inferences. In this study, we have established for the first time the link between market position in the trade network with the price at which animals were sold. If such a link is confirmed, it would provide an additional tool to policy makers for identifying highly connected markets upon which surveillance and control activities may be implemented.

In the current study, the size of the available dataset allowed us to apply an iterative modeling approach to assess the variability of the model and increase the confidence in the robustness and validity of the relationship between the price of cattle and the putative drivers of price formation (52). However, the price of cattle across the study area was not totally explained by our model, with 52.6% (range: 50.7–54.4%) of the variations still unaccounted for. In particular, our model tends to overestimate the price of young bulls but underestimates the price of adult males. Both phenotypic and breed characteristics of the animals involved in transactions, when adjusted with local and temporal factors, have the potential to explain a large proportion (>60%) of variations in their selling price (53, 54). For example, cattle that appear lighter, sick or having physical impairments are likely to be sold at a discounted price, whereas animals with large humps (which is a delicacy in Cameroon), or particular breeds such as the Gudali (1), would be sold at a large premium. Alternatively, requiring cattle to travel long distances (either on foot or using a vehicle) to be sold at market has been associated with larger livestock prices in SSA (21), accounting for up to 70% of the transaction costs (19). Although including these animal-level details (e.g., transport, breed, body condition) in the analysis would have been a huge refinement to our understanding of price variations among cattle sold in Cameroon and would have allowed comparisons with other studies, these data were not available in the records from the markets involved in our study.

In this study, we assumed that breed distributions in Cameroon are related to administrative Divisions. As such, we expected that the geographical drivers (captured as the Divisions in the model) would account for the influence of breed and cultural factors on cattle prices. Interestingly, most of the markets showing significant deviation from the average price (i.e., random effects) were in the Vina Division (**Figure 4**) where the Gudali breed predominates and where access to transport infrastructure such as rail and more recently road is available. It is therefore likely that the variable Division would act a proxy and account for the influence of both breed and transport onto cattle prices. However, such information need to be ultimately recorded if we want to better understand the animal health status of cattle at markets, as well as better understand how cattle prices are formed.

Limitations in the availability of local and regional data on the price of cattle sold in markets also limited our ability to assess whether price in other regions of the country, or in other neighboring countries, were influencing the price of cattle sold in the study area (40). As such, it was not possible to assess the level of protection of the local trading system against external market shocks (41) and, thus, evaluate the level of market integration of the cattle trading system in the study area. Consequently, we were not able to evaluate the level of vulnerability of stakeholders involved in the local and regional cattle industry (in broad term) against external factors. Again, improving data collection procedures at livestock markets is of the utmost importance if we want to develop integrated animal health management programmes. However, rather than being restricted to our study area, prices at which cattle are sold need to be consistently and regularly recorded (as well as centrally kept) in the wider SSA to facilitate such a study.

In conclusion, we have shown that cattle prices in Cameroon vary between commodity types, geographical areas, and the position of the market in the national trading network. However, there remains a large unexplained component in the price formation that may be due to breed, body condition, culture, and access to transport that are not currently captured in the trade records from markets. In addition, this study was not able to include markets in other administrative Regions of Cameroon and in neighboring countries that may also have an impact on price, particularly when including market in urban centers in high consumption areas. Nevertheless, this study represents a milestone in better understanding the cattle trading system and price formation in a Central African country and provides valuable information for better design of animal health programmes and for epidemiologists to develop better dynamic mathematical models for exploring disease spread and the impact of alternative control measures.

ETHICS STATEMENT

This research was authorized by the Ministry of Livestock, Fisheries and Animal Industries (MINEPIA) and approved by the Cameroon Academy of Sciences. In the United Kingdom, approval was given by the Veterinary Ethical Review Committee of the Royal (Dick) Veterinary School (University of Edinburgh). All methods for data collection and gathering were performed in accordance with the relevant regulations and in compliance with the received guidelines.

AUTHOR CONTRIBUTIONS

PM, IH, VT, KM, and BB designed the data collection and the overall research programme; PM, VN, and SH performed the field work. PM, TP, IH, and BB designed the study. PM conducted the analyses. PM, GR, and TP interpreted the results and wrote the manuscript. GR, IH, KM. and BB revised and reviewed the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at http://www.frontiersin.org/articles/10.3389/fvets.2017.00244/full#supplementary-material.

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Benefit–Cost Analysis of Foot-and-Mouth Disease Vaccination at the Farm-Level in South Vietnam

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This study aimed to analyze the financial impact of foot-and-mouth disease (FMD) outbreaks in cattle at the farm-level and the benefit–cost ratio (BCR) of biannual vaccination strategy to prevent and eradicate FMD for cattle in South Vietnam. Production data were collected from 49 small-scale dairy farms, 15 large-scale dairy farms, and 249 beef farms of Long An and Tay Ninh province using a questionaire. Financial data of FMD impacts were collected using participatory tools in 37 villages of Long An province. The net present value, i.e., the difference between the benefits (additional revenue and saved costs) and costs (additional costs and revenue foregone), of FMD vaccination in large-scale dairy farms was 2.8 times higher than in small-scale dairy farms and 20 times higher than in beef farms. The BCR of FMD vaccination over 1 year in large-scale dairy farms, small-scale dairy farms, and beef farms were 11.6 [95% confidence interval (95% CI) 6.42–16.45], 9.93 (95% CI 3.45–16.47), and 3.02 (95% CI 0.76–7.19), respectively. The sensitivity analysis showed that varying the vaccination cost had more effect on the BCR of cattle vaccination than varying the market price. This benefit-cost analysis of biannual vaccination strategy showed that investment in FMD prevention can be financially profitable, and therefore sustainable, for dairy farmers. For beef cattle, it is less certain that vaccination is profitable. Additional benefit-cost analysis study of vaccination strategies at the national-level would be required to evaluate and adapt the national strategy to achieve eradication of this disease in Vietnam.

Keywords: animal health economics, benefit-cost analysis, evaluation, financial analysis, foot-and-mouth disease, vaccination

INTRODUCTION

Foot-and-mouth disease (FMD) is recognized to heavily impact livestock production (1). The direct impact of this disease can be classified as two types: visible and invisible losses (1). The visible damages include draft power loss (2), milk production loss (1, 3), abortion (4), death, and decrease in livestock product value (2). The invisible losses include reduction in fertility, delay in the sale of animals and livestock products, change in farm structure (resulting from deaths, decreased

Abbreviations: NPV, net present value; BCA, Benefit-cost analysis; BCR, benefit–cost ratio; FMD, foot-and-mouth disease; kVND, thousands of Vietnam Dong (Vietnamese currency); NA, not applicable.

parturition rate and delayed sales), and reduced access to the market (1). Moreover, FMD causes additional expenditures (indirect impacts) in disease control such as vaccination, post-vaccination monitoring, movements control, diagnostic, and surveillance (1). The impact of FMD is especially meaningful to small producers as it threatens their livelihood and food security (5). In Laos, annual losses due to FMD infection were reported to reach between 16 and 60% of the annual household income (6). In Vietnam, Forman et al. (7) recorded net losses due to FMD ranged between 10 and 32% of the total annual household income. In Cambodia, FMD was shown to reduce the household income by more than 11% every year (2). Vaccination has been recognized as a helpful tool to control FMD and is an essential part of the progressive FMD control pathway from the World Health Organisation (1, 8). In Vietnam, this tool has been applied since 2006 to improve FMD control at a national-level with the objective of reaching eradication by 2020. Currently, the two major FMD serotypes O and A are circulating in Vietnam (9). Vaccines which are currently in use in a biannual strategy are either monovalent (targeting serotype O) or bivalent (targeting serotype O and A). Vaccination is usually implemented twice a year in March–April and September–October (two vaccination campaigns per year). According to the epidemiological situation, provinces of Vietnam are classified into two zones: high-risk (subdivided into control and buffer) and low-risk zones (9, 10). As the risk of emergence is considered to be high in high-risk zone, the program targets mainly those areas. The control zone (high-risk) consists of eight provinces along the northern border, six provinces along the southwest border, between Vietnam and Cambodia, and five provinces located on the border with Laos and the Central Highlands region. The buffer zone (high-risk) consists of 90 provinces adjacent to the control zone. The low-risk zone consists of nine provinces in the Red River Delta region, four important export provinces along the North Central Coast (Nghe An, Thanh Hoa) in the Red River Delta region (Ninh Binh, Vinh Phuc), nine provinces in the Mekong Delta region, and three provinces in the South-East region and Ho Chi Minh City (9, 10). Vaccination is partly supported by the government. In the control and the buffer zones, vaccine fees are financed up to 100% (free vaccine twice a year) and 50% (free vaccine for the first campaign in March–April, vaccine bought by farmers for the second campaign in September–October) of their costs, respectively, by the national budget, while the labor cost of the commune's veterinarian is paid for by the local authorities. In low-risk zones, these fees are paid for by the local authorities (9, 10). However, this strategy is facing many logistical and economic constraints, i.e., lack of strict implementation and sustainability at the farm-level and reduced perception of FMD risk after several years without outbreak. Therefore, its effectiveness, in terms of vaccine coverage and disease control, has not been achieved, i.e., outbreaks are still continuously recorded (9, 10).

Benefit–cost analysis (BCA) is a commonly used analytical framework that supports the decision-making process in animal disease control (11). When the farmers face a particular livestock health issue, BCA allows comparisons between the cost incurred and the benefit derived from the different available control methods in terms of financial return (11) or livelihood and overall wellbeing (12). The outputs of a BCA would not only foster the vaccination policy review and modification at a national-level but also provide evidence which can encourage farmers' participation in the campaign. In Ethiopia, it was reported that the national targeted vaccination program was the most economically beneficial strategy, with a median benefit–cost ratio (BCR) of 4.29 (13). In Cambodia, Young et al. (14) estimated that the implementation of a biannual FMD vaccination campaign in large ruminants during 5 years had a BCR of 1.4 (95% CI 0.96–2.20). In South Sudan, the BCR of FMD vaccination was estimated at 11.5 (3). Despite its relevance, no BCA for FMD vaccination at the farm-level has so far been completed in Vietnam. The aim of this study was to analyze the FMD financial impact at the farm-level in Vietnam and the BCR of the vaccination program to address this knowledge gap and better inform policy decision.

MATERIALS AND METHODS

Study Area

The study was performed in five districts of Long An province (i.e., Tan Hung, Vinh Hung, Kien Tuong, Duc Hoa, Duc Hue) and three districts of Tay Ninh province (i.e., Trang Bang, Chau Thanh, Go Dau). These districts were selected, in agreement with the sub-Department of Animal Health of the provinces under study, based on the importance of their livestock production, their proximity to the Cambodian border, the importance of animal movements from these districts to other provinces and countries, and their location in the high-risk area for FMD. The limited area of study as well as cattle population density were visualized in **Figure 1**. Two types of survey were implemented in the field. The general survey aimed to collect farm production and farm management and was conducted in eight districts of two provinces as mentioned above. The second survey named financial impact survey was done in only two districts of Long An province in the framework of another study implemented in the same period ((15), submitted manuscripts).

Data Collection Process

A questionnaire-based survey (general survey) was performed to collect general information on farm production and farm management practices, such as the number of cattle per farm, the number of calves and adult cattle per farm, the unit price of one dose of a bivalent vaccine, the cattle live weight price per kg, the price of an insemination service, and the milk price per liter. This survey was performed from June to October 2014 in the eight districts of the study area as mentioned above, with the help of a group of 15 veterinary students from Nong Lam University, Ho Chi Minh City. The students were trained about the questionnaire structure and face-to-face interview method by two certified lecturers from Nong Lam University 1 month before performing the field survey. Farmer within two types of cattle production (dairy and beef) in eight districts mentioned above were invited to participated in questionnaire-based survey. The total number of interviewed farms per district was based on the cattle population density in each district. A stratified sampling for farms selection was performed based on the type of cattle

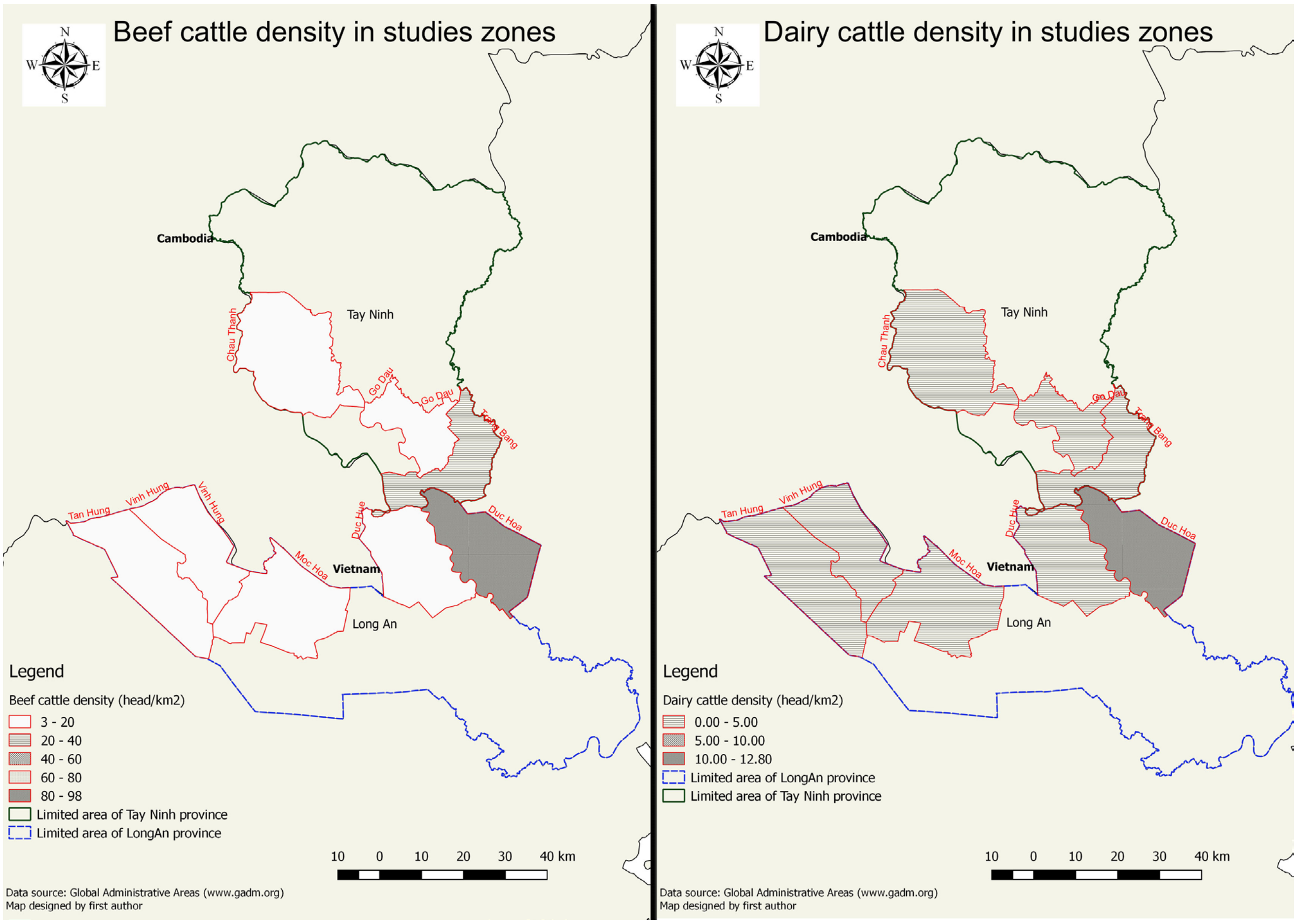

FIGURE 1 | Cattle population density in eights districts under study (left: beef cattle; right: dairy cattle).

production (dairy or beef) with a limit of 10 questionnaires per production type per village.

Data about the financial impact of FMD (relative costs of control FMD case in cattle at the farm-level) were collected in farms with FMD suspicion which were detected during study period (animal having clinical signs of the disease that were recognized by farmer). Indeed, a series of focus group and individual interviews took place from November 2015 to April 2016 in the framework of a study on the topic of participatory surveillance in sentinel villages in Duc Hoa and Duc Hue district of Long An province. Focus group interviews of 10–15 farmers per village were implemented to identify farms present suspected cases of FMD. Those suspected farms were then being the subject to individual semi-structured interviews to collect data on FMD financial impact. The results of the participatory surveillance study were reported apart, and financial impact data collected from infected farms were presented and used in this paper. In those farms, general data on disease management, control methods, disease impact, and all related costs were first collected using a standardized questionnaire. The first part of the questionnaire included general questions on the number of cattle at risk, number of disease cases, number of deaths due to the disease, number of premature slaughters, number of cattle destroyed, number of cattle vaccinated, vaccine type used, and actual vaccination practices applied in the farm. The second part of the survey contained questions on the financial costs associated with FMD infections. Farmers were asked to describe the cost associated with each control measure applied in their farm such as treatment with modern and/or local medicine, disinfection, emergency sale or slaughter of infected (dead) animals, emergency vaccination of unvaccinated cattle in case of outbreak, as well as the financial cost of disease-related increase in abortion and decrease in milk production. The value of an infected (dead) animal was based on the price paid to farmers by traders at the time of the survey. The value of new-born calves was estimated by farmers based on feed intake and the sale price of healthy calves sold at 3 months of age.

Calculation of Incidence Rates and Incidence Risks of FMD in Cattle Farms in the Study Area

It was assumed that cattle infected once by FMD did not get infected later in their productive life. A FMD sero-prevalence of 60% at the animal-level in infected herds was measured in the study area (unpublished data). It was assumed that antibodies against FMD are detected in cattle up to 3 years postinfection (16).

The incidence rate of FMD was calculated using the following formula:

$$\lambda = \frac{-\log(1 - p_x)}{x}. \quad (1)$$

With: λ being the herd incidence rate of FMD, p_x the measured sero-prevalence in the cattle population, x the duration of FMD immunity in cattle (the period during which FMD antibody are detected after infection).

The proportion of slaughtered cattle that have been infected during their whole lifetime is:

$$p_T = 1 - e^{-\lambda T}. \quad (2)$$

With: T being the average duration of a cattle productive life (or age at slaughter) (6 years in dairy cattle, 12 years in beef cattle).

The fraction of the cattle population of a given cattle farm being infected by FMD over 1 year (the number of cattle infected over 1 year divided by the total herd size) is:

$$p_y = \frac{1 - e^{-\lambda T}}{T}. \quad (3)$$

The proportion of calves being infected by FMD over 1 year in a given farm (the number of calves infected over 1 year divided by the total calve population of the herd) is:

$$p_y = \frac{1 - e^{-\lambda T_c}}{T_c}. \quad (4)$$

With T_c the age cattle become adults (the age of first calving for females).

The proportion of adult cattle being infected by FMD over 1 year in a given farm (the number of adult cattle infected over 1 year divided by the total adult cattle population of the herd) is:

$$p_{ya} = \frac{e^{-\lambda T_c} - e^{-\lambda T_c}}{T - T_c}. \quad (5)$$

Partial Budget Analysis at Farm-Level

The analysis was based on the methodological framework proposed by Dijkhuizen et al. (17) and Rushton et al. (18), modified and adapted to the study context. The components used in the partial budget analysis are described below. The analysis includes additional revenue, foregone revenue, additional costs, and saved costs, compares "*status quo*" scenario with no FMD vaccination to an alternative scenario where FMD vaccination is applied twice a year. The formula for calculation of additional costs, saved costs, additional revenue, and foregone revenue as well as their subcomponents and used variables are detailed in **Table 1**.

Additional costs represent costs incurred in the alternative scenario that are not present in the "*status quo*" scenario. It includes vaccine price (vac) and labor cost of vaccination practice (labour) that farmer needs to pay. Extra feed and labor cost of farming more cattle in farm because of the reduced mortality and drop in abortion was not included in our analysis as all animals were assumed to be replaced in "*status quo*" scenario.

TABLE 1 | Formula and variables used in the partial budget analysis of foot-and-mouth disease (FMD) vaccination in South Vietnam.

Formula and variables
Additional costs = labour + vac = (labour.ani + p.vac) × N.j.k × n.p
Labour labour cost of vaccination; vac: expenditure in vaccine purchase; labour.ani: labour cost per injection per cattle; p.vac: unit price of one dose of a bivalent vaccine; N.j.k: number of cattle per farm depending on scale *j* and farm type *k*; n.p: number of injections per year
Saved costs = Treat.cost.k + rep.a.d + rep.c.d + e.vac.c + Ser.loss + Treat.cost.k = p_y × (Treat.mod.k + Treat.loc.k) × N.j.k × morb.k + rep.a.d = p_{ya} × (p.cow.h − p.cow.d) × N.a.jk × Mort.k + rep.c.d = p_{yc} × (p.calf.h − p.calf.d) × N.ca.jk × Mort.k + e.vac.c = p_{ya} × (labour.ani + p.vac) × (N.jk − N.ca.jk) × 2 × Morb.k + Ser.loss = p_{ya} × N.a.jk × per.cow.ges × Abor.FMD × no.ser.ges.i × P.ser × Morb.k
2: vaccine injections are performed at 28 days interval; e.vac.c: cost of emergency vaccination over the considered period; Morb.k: morbidity rate in case of FMD outbreak; N.a.jk: number of adult cattle per batch; N.ca.jk: number of calf per batch; N.j.k: the number of animal per batch (all cattle in the same production cycle); (N.jk − N.ca.jk): number of adult animal in scale *j* and farm type *k* in emergency vaccination; no.ser.ges.i: the average number of artificial or natural insemination service performed by veterinarians for each cow to become pregnant; p.cow.h: value of a healthy adult cattle p.cow.d: value of a dead or treated cattle p_{yc}: proportion of calves being infected by FMD over 1 year (calculated using Eq. 4), p.calf.h: value of a healthy calf, p.calf.d: value of a dead/treated calf; p_y: proportion of a given cattle farm being infected by FMD over 1 year (calculated using Eq. 3), p_{ya}: proportion of adult cattle being infected by FMD over 1 year (calculated using Eq. 5); P.Ser: average price of an insemination service. rep.a.d(rep.c.d): the cost of replacing adult cattle (calf) in case of death over the considered period; Ser.loss: the cost of additional insemination services used due to FMD over the considered period; Treat.cost.k: cost of FMD treatment with modern and indigenous medicine over the considered period; Treat.mod.k (Treat.loc.k): cost of treatment with modern (indigenous) medicine per affected cattle during the outbreak period
Additional revenue = M.prod + W.h.a + W.extra + Abor.red + M.prod = p_{ya} × t.ill × M × P.milk × N.a.jk × per.cow × Morb.k + W.h.a = p_y × t.ill × dwg × p.liveW × N.jk × Morb.k. + W.loss = p_T × cull.rate × per.W.loss × W.cow.h × p.liveW × N.jk × (Morb.k − Mort.k) + Abor.loss = p_{ya} × N.a.jk × per.cow.ges × no.calves.prod × Abor.FMD × p.n.calf × Morb.k
Abor.FMD: the increase in abortion rate due to FMD infection, Abor.red: additional cattle raised value due to less abortion cull.rate being the proportion of the cattle farm being culled each year (it is the inverse of the age at maturity—*cull* rate = $\frac{1}{T}$); dwg: average daily weight gain; M: average quantity of milk produced per lactating cow per day; M.prod: additional milk production value; no.calves.prod = $\frac{\text{duration of a year in day}}{\text{overall mean of calving interval in day (ci)}}$: Number of calves produced per cow in 1 year;

(*Continued*)

TABLE 1 | Continued

Formula and variables
N.a.jk: number of adult cows in farm; P.milk: price of one liter of milk; per.cow.lac: percentage of lactating cows in the farm (including cow with pregnant and lactating at the same time); p.liveW: price of a live weight in kilogram; p_T: proportion of slaughtered cattle having been infected during their whole lifetime (calculated in Eq. 1); per.W.loss:average percentage of weight loss of cattle due to FMD; p.liveW: live weight price (per kilogram); per.cow.ges: percentage of adult cattle which are gestating cow in the farm; p.n.calf: price of a new-born calf estimated by farmer; t.ill: average duration of illness due to FMD; W.h.a: additional weight gain value; W. extra: additional cattle raised value due to lower mortality; W.cow.h: average weight of a healthy cow at sale time in kilogram.
$\text{Foregone revenue} = \text{inc.a.d} + \text{inc.c.d}$ $+\,\text{inc.a.d} = p_{ya} \times \text{p.cow.d} \times \text{N.a.jk} \times \text{Mort.a}$ $+\,\text{inc.c.d} = p_{yc} \times \text{p.calf.d} \times \text{N.ca.jk} \times \text{Mort.c.}$ inc.a.d: income of selling dead/sick adult cattle; inc.c.d: income of selling dead/sick calves.

Saved (avoided) costs represent costs incurred in the "*status quo*" scenario that are avoided in the alternative scenario. It includes cost of disease treatment (Treat.cost.k) with modern and local medicine per cattle, cost of replacing adult cattle (rep.a.d) and calves (rep.c.d) in case of death over the considered period, cost of emergency vaccination (e.vac.c), and cost of additional insemination services (ser.loss). Cost of movement restriction was excluded because feed intake during delay time could not be collected. Cost of disinfection was also excluded because the relative data could not be quantified.

Additional revenue represents the revenue generated in the alternative scenario which is not present in the "*status quo*" scenario. It includes revenue gain from additional milk production from healthy cattle (M.prod) from selling healthy cattle at higher price due to higher weight compared to lower weight of infected (weight lost during sick period) (W.h.a), additional cattle raised and sold when there is less mortality (W.extra), and less abortion (Abor.red) due to FMD infection. We did not include the additional revenue from additional milk production resulting from the reduction of cows' mortality. Indeed, we did not have the necessary data on the additional quantity of feed consumed to sustain this increased milk production.

Subsidies of government, which generally covered between 50 and 100% of the vaccination costs, were not taken into account in the calculation since the analysis was done at farm-level, without considering any contribution from the government, which returned a more conservative result.

Foregone revenue represents the revenue generated in the "*status quo*" scenario which is not present in the alternative scenario. It includes revenue lost due to adverse impacts of vaccination on productivity such as decreased milk production, decreased daily weight gain, and impact on reproduction such as abortion due to stress caused by bad practice. It also includes the revenue from selling dead or sick cattle and calves (inc.a.d + inc.c.d) at lower price. As data were missing foregone revenue due to adverse vaccination effects vaccination was considered to be null. It was also assumed the vaccination was perfectly implemented, and did not cause any adverse effect due to stress.

TABLE 2 | Proposed scenarios for sensitivity analysis of benefit–cost ratio.

Scenario	Vaccination Cost	Milk and cattle market value
C1	Increased by 25%	NA
C2	Increased by 50%	NA
C3	NA	Decreased by 10%
C4	NA	Decreased by 20%
C5	Increased by 25%	Decreased by 10%
C6	Increased by 25%	Decreased by 20%
C7	Increased by 50%	Decreased by 10%
C8	Increased by 50%	Decreased by 20%

NA, not applicable.

Benefit–Cost Analysis

Partial budget analysis was used to estimate the benefits (additional revenue and saved costs) and costs (additional costs and revenue foregone) of using vaccination method of one given farm to prevent FMD over a 1-year period. The total benefit of the vaccination program is the sum of the additional revenue and saved costs while the total cost is the sum of the foregone revenue and additional costs.

The net present value (NPV) of the proposed change in disease control strategy observed in alternative scenario compared to "*status quo*" scenario was calculated on an individual farm for the period of 1 year as follow:

$$\text{Net present value} = (\text{saved cost} + \text{additional revenue}) - (\text{additional cost} + \text{foregone revenue}). \quad (6)$$

The BCR between alternative scenario and "*status quo*" scenario was also computed on an individual farm using following formula:

$$\text{Benefit} - \text{cost ratio} = (\text{saved cost} + \text{additional revenue}) / (\text{additional cost} + \text{foregone revenue}). \quad (7)$$

Benefit–cost ratio was calculated for three types of production: large-scale and small-scale dairy farm and small-scale beef farm. The distinction in scale was based on the classification used in national program of vaccination. In this program, farm present less than twenty animals was classified as small, farm within more than twenty animal was considered as large (10).

Sensitivity Analysis

The sensitivity analysis for benefit–cost of FMD vaccination was performed by changing vaccination cost and market prices of sold cattle and milk. This analysis was performed to understand the variation in benefit–cost and the influence of the variance of these parameters on the BCR associated with FMD vaccination. Eight scenarios (C1–C8) were tested by changing vaccination cost and/or market value of milk and slaughtered cattle (**Table 2**). In C1 and C2, vaccination cost was increased by 25 and 50%, respectively. In C3 and C4, the market price of cattle and milk were decreased by 10 and 20%, respectively. From C5 to C8, changes in both parameters were performed. The increase in vaccination cost of 25% and 50% was based on hypothesis that farmer would rather use trivalent vaccine in the future if the presence of the third serotype would be confirmed (vaccination cost increase of 25%) or farmer would practice vaccination more than twice a year (vaccination cost increase of 50%). The decrease in market value of 10 and 20% was based on market tendency of milk and meat product. The milk price tends to be decreased because of excess supply source and meat price also decreased because of the competition of imported meat from India and Australia.

Assumptions Used in the Cost–Benefit Analysis

Some parameters used in the BCA were taken from the literature (**Table 3**) because those parameters could not be collected from the field studies. It was assumed that all dairy and beef farms used Holstein-Friesian crossbreeds and Red Sindhi crossbreeds, respectively, based on Vo (19) and Hoang (20). The duration of the productive life of dairy and beef cattle were considered to be 6 and 12 years, respectively. Subsequently, the BCA was calculated for 1 year but took into consideration the duration of the productive life of dairy and beef cattle in the calculation of FMD incidence risks to be able to compare the result for the two types of production. Milk price was based on its quality and was considered as being the same for every lactating cow. Vaccination was considered to be applied within the best practices and to be match with OIE standard for FMD vaccination. Vaccine should contain at least three PD50 (50% of protective Dose) which corresponded to 78% protection using protection against generalization test (21). Vaccination was considered not causing stress in cattle and, therefore, not impacting abortion rate. Only acute FMD was taken into consideration in this analysis while chronic FMD was excluded. The average FMD mortality in adult cattle was estimated at 7.3% (2) instead of the observed value in the field (12%) after consulting expert's opinion. These values were also added in sensitivity analysis due to uncertainty nature of the data.

Data Analysis

All analysis was performed using R software version 3.3.1. A framework of calculation NPV and BCR which included functions and formula described above and in **Table 1** was developed in R environment for three production types. The uncertainty over the value of the parameters used in the analysis was addressed through a Monte Carlo procedure. The probability distribution of the NPVs and BCRs where obtained by sampling 1,000 values of parameters from their respective assumed probability distributions, using a random Latin Hypercube sampling procedure (Carnell R. lhs: Latin Hypercube Samples. R package version 0.14 2016. Available from: https://CRAN.R-project.org/package=lhs.). According to the information available, different types of data were used in the analysis. Triangle distribution data was available for value of a healthy calf/cow, value of a dead or after treatment calf/cow, vaccination labor cost, cost of treatment with indigenous/modern medicine, number of calves/adults cattle per farm according to each production types, number of animal per farm, mortality rate in a farm for calf. Normal distribution is seen in data of abortion rate due to FMD, volume of milk produced

TABLE 3 | Input data and references used to estimate foot-and-mouth disease (FMD) vaccination benefits and costs for farmers.

Input data (unit)	Production type		Description and/ or data sources	Abbreviation
	Dairy cattle farms	Beef cattle farms		
Abortion rate due to FMD (%)	10 ± 2.3[a]		Senturk and Yalcin (4)	Abor.FMD
Average number of milk produced per cow per day (liter)	11.4 ± 0.3[a]	NA	Le and Nguyen (22)	M
Average weight of a healthy animal (kg)	418 ± 6.25[a]	284.6 ± 35[a]	Based on Dinh (23), for beef, Le and Nguyen (22) for dairy	W.cow.h
Average weight loss when infected (%)	24 ± 1.16[a]		Young (2)	per.W.loss
Duration of illness (days)	11.1 ± 1.33[a]		Young (2)	t.ill
Estimated mean daily weigh gain (kg/day)	0.5[c]	0.36[c]	Dinh (24) for dairy, Dinh (23) for beef	Dwg
Median calving interval (days)	441[c]	390[c]	Dinh (24) for dairy, Dinh (23) for beef	Ci
Age of first calving (years)	2.19[c]	2.13[c]	Dinh (24) for dairy, Dinh (23) for beef	T_C
Number of average service for a cow being gestation (time)	2 ± 0.11[a]		(22)	no.ser.ges.i
Percentage of lactation cow in farm (%)	50[c]	NA	Vo et al. (25)	per.cow.lac
Percentage of pregnant cow in farm (%)	58[c]	56.31[c]	Calculation based on data of Vo et al. (25) for dairy, Dinh (23) for beef	per.cow.ges
Mortality rate in a farm (%) adult cattle[f]	7.3[c,d]–12[c,e]		(2)	Mort.a
Incidence rate of FMD at farm level	30 (26.2–33.7)[b]	30 (26.2–33.7)[b]	(26)	λ
Duration of FMD immunity in cattle (year)	3[c]	3[c]	(16)	*x*
Average duration of a cattle productive life (or age at slaughter)	6[c]	12[c]	Author estimation	T

NA, not applicable.
Type of probability distribution.
[a]Normal distribution: mean ± SD.
[b]Normal distribution: mean (CI 95%).
[c]Data available as mean value only.
[d]Value from literature.
[e]Value issued from financial impact survey.
[f]Two values were used in sensitivity analysis.

per cow per day, weight of a healthy animal, weight loss when being infected, duration of illness, number of service for a cow being gestation, incidence rate of FMD at the herd-level. Value of a new-born calf and mortality rate of adult animal were available only in uniform distribution (more details could be found in **Tables 3–6**). BCRs were consistently higher than 1 indicated that the considered investment in FMD vaccination was worthwhile. Data were calculated using "reshape2" (27) and reported using "knitr" package (28).

Ethical Considerations

Our study was approved by the local authorities (sub-Department of Animal Health of Long An). Ethical considerations were properly taken into account. In Vietnam, this study was considered as a common study on animal health and therefore no ethical committee is provided by the national authorities.

Informed consent was obtained from all farmers included in the study. As for each individual interview, each participant signed a written consent to be part of this study.

RESULTS

Partial Analysis of FMD Vaccination

General Survey

Livestock production data which were collected by questionnaire from 49 small-scale dairy farms, 15 large-scale dairy farms, and 249 beef farms located in 37 villages of eight districts were summarized in **Table 4**. While beef farms were widely distributed in eight districts under study, dairy farms were mainly practiced in Duc Hoa district of Long An province and Trang Bang district of Tay Ninh province.

Financial Impact Survey

A total of 69 focus group interviews were organized in 32 villages of Duc Hoa and Duc Hue districts with the participation of 702 farmers. 129 farms located in 14 villages were then detected as suspected farms and being subject for individual interview using financial impact survey. The investigation demonstrated that in case of being infected by FMD, 43.8% of the cattle in the three production types received treatment with only modern medicine rather than local medicine (11.5%) or with both modern and local medicine (20.9%). Local medicine was especially used in the beef production type (92.6% of cases). The incidence rates and incidence risks of FMD in cattle farm estimated from the collected data and literature using Eqs 1–5 were presented in **Table 5**. Other data on the financial impact of FMD outbreaks at the farm-level was summarized in **Table 6**.

TABLE 4 | Description of the animal production parameters from the study area extracted from the general survey.

Variables	Dairy cattle farm	Beef cattle farm	Abbreviation
Number of adult cattle per farm, small-scale	8 (1–19)[a]	2 (1–16)[a]	N.a.jk
Number of adult cattle per farm, large-scale	19 (13–41)[a]	NA	
Number of calf per farm, small-scale	1 (1–8)[a]	11 (1–10)[a]	N.calf. jk
Number of calf per farm, large-scale	1 (1–9)[a]	NA	
Number of animal per farm, small-scale (<20 heads)	12 (2–20)[a]	2 (1–16)[a]	N.j.k
Number of animal per farm, large-scale (>20 heads)	25 (21–50)[a]	NA	

NA, not applicable; type of probability distribution: [a]triangle distribution: mode (min–max).

Partial Analysis of FMD Vaccination

The NPV of FMD vaccination versus "*status quo*" scenario was always positive in dairy farms. However, in beef farms, the 95% CI of the NPV encompassed 0, meaning that the NPV of vaccination could be negative (**Table 7**), or it is not sure whether vaccination is profitable in beef farms. The mean NPV was highest for the large-scale dairy farms [44,438 kVND per year (95% CI 25,175–65,467)], followed by small-scale dairy farms [15,664 kVND per year (95% CI 4,703–27,202)], and beef farms [1,499 kVND per year (95% CI −2,896 to 5,142)] (**Table 7**). The average value of additional revenue in large-scale dairy farms was 48,548 kVND per farm per year, which was 2.8 times higher than in small-scale dairy farms and around 19 times higher than in small-scale beef farms.

BCA of FMD Vaccination and Sensitivity Analysis

All the parameters estimated and used in the analysis are presented in **Table 7**. The BCR was highest in large-scale dairy farm (5.74 95% CI 2.83–12.34), followed by small-scale dairy farm [5.24 (95% CI 1.88–11.61)], and it was lowest in small-scale beef farm [1.95 (95% CI 0.31–4.91)] (**Figure 2**; Table S1 in Supplementary Material). The sensitivity analysis showed that the effect of varying the vaccine cost on the resulting vaccination BCR was higher in beef farms than in dairy farms. However, the effect of varying market prices on the resulting vaccination BCR was higher in dairy farms than in beef farms (**Figure 2**; Table 1 in Supplementary Material). For three production types, changes in market value had more impact on the BCR than changes in vaccination cost. The BCR of vaccination in dairy farms was always higher than 1 in the 8 proposed scenarios—increased vaccination costs and/or

TABLE 5 | Description of the estimated parameters used for the benefit-cost calculation of foot and mouth disease extracted from the general survey.

Parameters	Dairy cattle farms	Beef cattle farms	Abbreviation
Proportion of slaughtered cattle having been infected during their whole lifetime	0.84	0.97	p_T
Proportion of a given cattle farm being infected by foot-and-mouth disease (FMD) over 1 year	0.14	0.08	p_y
Proportion of calves being infected by FMD over 1 year	0.22	0.22	p_{yc}
Proportion of adult cattle being infected by FMD over 1 year	0.09	0.05	p_{ya}

TABLE 6 | Description of the parameters used for the benefit-cost calculation of foot-and-mouth disease extracted from the financial impact survey.

Input data	*n*	Dairy cattle farm	Beef cattle farm	Abbreviation
Cost of treatment with indigenous medicine per animal (kVND/head)	46	100 (5–875)[a]		Treat.loc.k
Cost of treatment with modern medicine per animal	90	300 (30–2,300)[a]		Treat.mod.k
Value of a dead calf or after treatment (kVND/head) ≤6 months	13	0 (0–14,800)[a]		p.calf.d
Value of a dead or sold cow after treatment (kVND/head)	15	45,000 (700–45,000)[a]		p.cow.d
Value of a healthy calf (kVND/head) ≤6 months	11	10,000 (10,000–19,000)[a]		p.calf.h
Value of a healthy cow (kVND/head)	15	35,000 (18,000–55,000)[a]		p.cow.h
Labor cost per injection (kVND/head)	NA	4 (4–30)[a]		labor.vac
Morbidity in a farm (%) (*n* = 129)	129	79	54	Morb.k
Mortality rate in a farm (%) for calf	8	18 (0–50)[a]		Mort.c
Number of possible calves produced per cow in 1 year	NA	0.83	0.94	no.calves.prod
Price of 1 dose of bivalence vaccine (kVND/dose)	NA	37		p.vac
Price of 1 kg live weight (kVND), value in Dec 2015	NA	140		p.liveW
Price of one service (kVND/time)	184	173		P.Ser
Price of 1 liter of milk (kVND/liter), value in Dec 2015	NA	13.5	NA	P.Milk

Type of probability distribution: [a]triangle distribution: mode (min–max).
kVND, thousands of Vietnam Dong (Vietnamese currency).

TABLE 7 | Partial budget analysis results according to the different production types (small-scale dairy cattle farms, large-scale dairy cattle farms, and small-scale beef cattle farms).[a]

	Small-scale dairy farms	Large-scale dairy cattle farms	Small-scale beef cattle farms
Additional cost (kVND)	1,120 (459–1,922)	3,193 (2,075–5,289)	691 (177–1,548)
Foregone revenue (kVND)	3,195 (868–6,401)	7,383 (1,542–14,437)	1,731 (238–3,966)
Saved cost (kVND)	2,739 (−17 to 6,227)	6,466 (−352 to 14,633)	1,346 (−814 to 3,667)
Additional revenue (kVND)	17,240 (6,523–26,603)	48,548 (33,407–69,647)	2,576 (580–5,609)
Net present value (kVND)	15,664 (4,703–27,202)	44,438 (25,175–65,467)	1,499 (−2,896 to 5,142)

[a]Result of Monte Carlo Simulation: mean (CI 95%).
kVND: thousands of Vietnam Dong (Vietnamese currency).

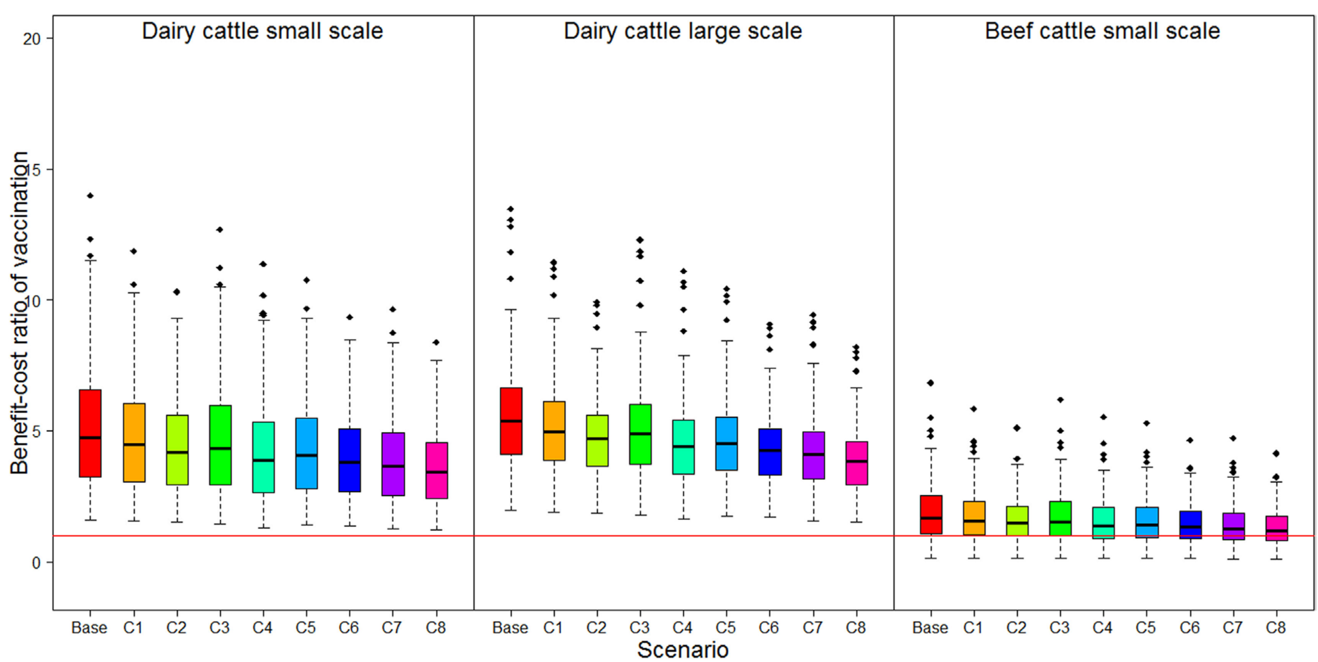

FIGURE 2 | Benefit–cost ratio and sensibility analysis results of vaccination strategy for foot-and-mouth disease in three production types. Base: benefit–cost ratio (BCR) in real situation, C1–C8: proposed scenarios for sensitivity analysis detailed in **Table 2**. Red horizontal line: threshold of BCR.

decreased milk and/or cattle price. This implies that even at high vaccine price and low market value, FMD vaccination was still profitable. In small-scale beef farms, however, the 95% CI of the BCR included 1 in the 8 proposed scenarios, meaning that the FMD vaccination could be profitable or not depending on the value of the parameters.

DISCUSSION

In Vietnam, an important fraction of the national budget for FMD prevention and control is dedicated to vaccination, including delivery costs and subsidies for vaccine purchase, which vary from 50 to 100% of the vaccine price in high-risk areas. However, outbreaks are still continuously recorded (9). This observation raises concerns over the effectiveness of the vaccination program and its acceptability at the farm-level. The BCA demonstrated the financial interest for dairy cattle farmers of using vaccination to control FMD as, regardless of the used scenario, FMD vaccination was always profitable. For beef farmers, however, the financial profit derived from vaccination appeared weaker and uncertain, as the BCR could be higher or lower than 1 depending on parameters' value (e.g., the cost of replacing adult cattle or calf in case of death—rep.a.d or rep.c.d). The output of this study might be used to motivate dairy farmers to participate in vaccination campaigns. It also suggests that high FMD vaccination coverage may be more difficult to reach in the beef cattle sector than in the dairy cattle sector since the expected financial profit from FMD vaccination is much lower in farms of the former category. Yet, sufficient vaccination coverage needs to be reached in both sectors in order to control the disease at the national-level. The latter information may be used by decision makers to refine the national program of prevention and control of FMD in Vietnam. One way of improvement would be, for example, to provide stronger support to FMD vaccination in beef farms (e.g., with subsidies).

Decision to vaccinate depends on other factors such as real and perceived effectiveness of vaccination (11). Perception of farmers may vary with time and maintaining farmers' motivation to vaccinate is challenging since farmers always balance the risk of adverse consequences of diseases and cost of prevention. During the 6–12 years of cattle life, farmers can stop using vaccination at any moment if they perceive the probability of infection to be low enough; based on the information they get through official reports, media, and other sources of information. FMD surveillance data showed that in Vietnam, peaks of FMD outbreaks occurred every 2–3 years, and were negatively correlated with FMD vaccination coverage (26). During the survey we conducted, some farmers reported they refused to use vaccines because of their potential adverse effect on cattle such as increased risk of abortion, growth delay, and change in behavior (increased aggressiveness). Those side effects are mainly due to adverse vaccination administration practices, which are mentioned in another study (29).

Besides vaccination coverage, vaccination effectiveness also remains an important challenge in the Vietnamese context. A study in Tay Ninh province showed that despite a vaccination uptake of 85.4%, the sero-conversion in this province was only 60.6% (30). The imperfect application, storage, and delivery of vaccines can explain the relatively low effectiveness of vaccination (31). Past experiences of vaccine failure can discourage farmers from using it. Advantages of vaccination such as avoidance of animal slaughter, avoidance of carcass disposal, and decreased level of viral excretion (32) are highly relevant to developing countries. However, implementation issues linked to the man-power requirements for post vaccination surveillance and the need for multiple (cumulative) vaccine injections to achieve prophylactic protection (32) can also impair its effectiveness in the field.

Farmers' perception of the effectiveness of vaccination strongly affects their willingness to implement it (29). Education campaigns that aim at maintaining or enhance farmers' awareness of the benefits of FMD vaccination should be organized by veterinary authorities before each vaccination campaign (before April or September each year). While some costs related to the awareness campaigns are covered by authorities, like document preparation, invitation letter, speaker invitation, and television program, other costs such as document purchase and time spent in attending trainings, are supported by the farmers. It is estimated that in 1 year, 20 kVND in document and 115 kVND in labor time need to be spent by farmers for participating in education campaigns. Those costs increase the additional costs component and subsequently decrease the BCR of vaccination. Those additional costs might have more effect on the BCR of beef cattle than on the BCR of dairy cattle. Subsidies should be provided by the government to promote farmer's participation in trainings campaigns (technical document purchase and opportunity cost for attendance) in the form of subsidies should be added in this case. Vaccination in beef cattle could not be disregarded especially in a context of FMD eradication objective.

As specified in our assumptions, our study did not consider the specific impact of chronic FMD. Chronic FMD was reported to reduce milk production by 80% in affected cows (3, 33) and caused some clinical signs such as heat intolerance, infertility and, in general, poor productivity (34). Moreover, the chronic form of FMD usually starts around 4 weeks after the occurrence of the acute form (34), which makes its impact difficult to quantify as Vietnamese smallholder farmers usually do not systematically record cow performance. Quantifying losses due to chronic FMD would require long-term farm surveys. Further studies focusing on the economic impact of FMD at the local-level should consider the chronic form of FMD. A BCA study conducted in Sudan showed that chronic FMD is responsible for 28.2% of the total farm losses due to FMD (3). Therefore, including the impact of chronic FMD would probably increase the estimated saved costs and BCR of FMD vaccination.

It was assumed that cattle infected once by FMD did not get infected later in their productive life. Actually, cattle can be infected in several occasions by viruses of different serotypes (35). The predicted FMD incidences values are, therefore, probably underestimated. Correcting this bias would increase the BCR of FMD vaccination.

The government incentives for vaccination (subsidies) were not taken into account in this analysis in order to simplify the formula and make it conservative. Excluding such subsidies in our analysis enabled us to show that even if vaccination costs are fully supported by farmers, it still generates a positive net return. Currently, only vaccine purchases by small-scale farms are covered 100% by the subsidies whereas larger scale farms already support part of their vaccination costs (subsidies cover vaccine cost for up to 20 cattle). Dairy cattle farms get a higher BCR from FMD vaccination compared with beef farms as losses caused by FMD are higher in dairy farms than in beef farms (36) in the "*status quo*" scenario (without vaccination). Indeed, dairy cows have a higher replacement cost than beef cows, since they are more valuable in terms of performance and productivity.

The cost of the cattle movement restriction, which includes the additional feed intake of unsold animals during the restriction time, was not included in the analysis. According to the Vietnamese government regulation, movement restriction is implemented by the local veterinary authorities upon detection of the first FMD case in the area and is maintained all along the outbreak period. The ban ends 21 days after detection of the last FMD case (9). However, the application of this control measure at the local level might vary from one location to another and accurate data on the implementation of movement restrictions (or delay in selling time for affected farm) are difficult to collect in practice. The inclusion of such parameter would have increased the BCR of FMD vaccination.

The average cattle morbidity rate at the farm-level was around 60%, which is consistent with the results of a case study conducted in Ethiopia (37) but different to the results of another study which found morbidity rates reaching up to 100% (38). In our study, FMD cases were defined by the presence of clinical signs as recorded by farmers. Cattle present in infected farms that did not develop clinical signs were considered healthy. In reality, unapparent infections may occur in cattle whose susceptibility has been reduced by vaccination (38). Moreover, immunized animals subsequently exposed to FMD infection may become chronic carriers without developing clinical symptoms of the disease (16, 39, 40). On the other hand, endemic strains of FMD virus (e.g., serotype O in Vietnam) might cause mild forms of the disease in indigenous Zebu cattle in Asian endemic countries (38). Those aspects could lead to misdiagnosis by farmers and to an underestimation of the mean herd morbidity rate.

The mean FMD mortality in adult cattle observed in our study (12%) was considered higher than the one reported in the literature (7.3%) (2). As a consequence, the mortality variable in literature was used in our calculation instead of the one found by the survey. The possible explanation for the difference between literature data and the survey findings was described as follow. FMD infected animals may have secondary infections during recovery time (digestive troubles, hemorrhagic septicemia, etc.), which could delay or impede their recovery or even lead to their death in some instances. In case cattle do not recover well or die from a secondary infection, they are sent to slaughterhouse, as a consequence of FMD infection, even if FMDV does not directly cause their death. Subsequently, they were reported as death due to FMD to the research team. Moreover, high mortality was mainly observed in dairy farms using highly efficient cattle breeds which are more sensitive to the disease, in comparison to local breeds or crossbreeds used in beef farms. The both value of mortality rate (literature and survey finding) were used as part of the sensitivity analysis and lowering mortality could overestimate the BCR in dairy cattle.

CONCLUSION

Our study demonstrated that FMD biannual vaccination strategy is financially and clearly profitable for dairy cattle farmers in Vietnam even if all the vaccination costs are supported by the farmers but not in beef farm. It also showed that FMD vaccination is more profitable for dairy farmers than beef farmers. The results of this study could be used to refine the FMD control program and motivate farmers to use FMD vaccination. A similar study could also be implemented at the national-level to evaluate the BCR of the FMD vaccination strategy and adapt it to achieve the FMD eradication objective in Vietnam. This study's research framework and results are expected to become a firm ground for further research and awareness program.

AUTHOR CONTRIBUTIONS

DT, FG, AD, and MP designed the study, contributed to the analyses, and drafted the manuscript. DT and MP designed the data collection instrument and drafted the manuscript. VG and SB reviewed the results and drafted the manuscript. The manuscript has been read and approved by all authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at http://www.frontiersin.org/articles/10.3389/fvets.2018.00026/full#supplementary-material.

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Assessing Financial Impacts of Subclinical Mastitis on Colombian Dairy Farms

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Bovine mastitis is a dairy cattle disease with high economic impact. Subclinical mastitis (SCM) contributes to most of the financial losses. Colombia dairy sector accounts for 2.3% of the gross domestic product (GDP) and 24.3% of the livestock GDP. Milk production reaches 6,500 million liters/year from nearly 500,000 cattle farms and is mainly based on small-scale production systems. This study evaluates the financial impact of SCM and the potential for its control in three dairy farm strata in a region in Colombia. The objectives of the study were 1) to determine the perception of farmers about the SCM problem on their farms, 2) to assess prevalence and financial impact of SCM on farms and in the "Area five" sanitary region of the Bogota plateau, and 3) to assess costs and effectiveness of control methods of SCM. Information about disease management and decision-making process was obtained through a participatory epidemiology workshop and applying a semi-structured survey. A two-stage stratified cross sectional epidemiological study was conducted on dairy cattle from a region with approximately 400 farms and 12,000 cows, with a sample size of 55 farms. Prevalence of SCM was calculated by defining a cow as positive for the disease when any quarter had a somatic cell count (SCC) higher than 250 $\times 10^3$ cells/ml. The prevalence of SCM in cows was 55.2%; significant differences were found between strata. Assessment of the financial impact of SCM in terms of milk losses was conducted using spreadsheet models. Milk production losses per farm ranged from 1.3% to 13.5%, and the economic impact in the region was estimated over USD $800.000 per year. The financial impact was greater in small- and medium-sized farms than large farms, and it was associated with the severity of SCC per quarter. Principal component analysis showed interactions, irrespective of the individual effect, and suggested three main groups of control interventions: application of basic milking hygiene practices, increase in the level of hygiene practices and veterinary advice, and SCM diagnosis and dry-cow treatment. Lack of information on management and production at farms promotes intuitive decision-making. Further research for the deeper understanding of intervention costs and effectiveness is suggested.

Keywords: animal health economics, bovine mastitis, producers attitudes, production system, veterinary epidemiology

INTRODUCTION

Bovine mastitis is a disease with a high prevalence in dairy cattle worldwide with a major impact owing to economic losses caused at various levels of the dairy value chain (1–3). Mastitis is classified as clinical or subclinical depending on the visibility of effects of inflammation of the mammary gland. Subclinical mastitis (SCM) does not produce visible effects on udder or milk quality (4, 5) but has important effects on milk composition, mainly an increase in SCC (5, 6).

Studies to determine the economic impact of bovine mastitis have been conducted mainly in developed countries (1, 2, 7). Mastitis losses are due to reduced milk production, cost of treatments, and culling, accounting for 78%, 8%, and 14%, respectively (7). However, the economic impact of mastitis varies and should be calculated at the farm or herd level and depends on local, regional, epidemiological, managerial, and economic conditions (2, 3, 7, 8). Most losses are associated with SCM, defined as an increase in the content of SCC in milk, which many producers undervalue, owing to the lack of visible abnormalities in milk, which requires specific detection methods such as the California Mastitis Test (CMT) (4, 6). Additional disease losses are generated from disease management to the presence of both clinical and subclinical mastitis at farm (8–11).

The Food and Agriculture Organization (FAO) highlighted the importance of providing information on the economic dimension of the disease in resource-poor environments (12). In relation to SCM, FAO states that this hidden disease needs to be recognized early by producers, since its effective management does not depend solely on a simple recommendation but instead on multiple recommendations based on a better understanding of the disease.

In developing countries, the economic impact of SCM in small- and medium-sized farms varies according to the level of milk production per cow and the intensity of the production systems. In Costa Rica, milk production losses per cow with SCM were estimated at 1.6 kg day^{-1} for daily milk yield (4). In Ethiopian crossbreed dairy systems, milk production was reduced by 1.2%, 6.3%, and 33%, respectively, in quarters with CMT scores 1+, 2+, and 3+ (11). In smallholder dairy farms in Tanzania, with a prevalence of SCM of 46.2%, intra mammary antibiotics significantly reduced the proportion of bacteriologically positive quarters in the short-term (14 days post-infusion), but teat dipping had no detectable effect on bacteriological infection and CMT positive quarters (5).

In Colombia, total milk production is approximately 6,500 million tons/year, produced in dual-purpose systems (4.8 million cows) and specialized dairies (600,000 cows), with the latter mainly based on the Holstein breed. Less than half of the total produced milk (approximately 3,200 million tons/year) comes from the formal milk processing industry, including pasteurization. Milk is produced in small-scale production herds, 395,000 cattle producers, which represent 80% of the cattle producers in the country (13). The dairy sector in the country accounts for 2.3% of the gross domestic product (GDP) and 24.3% of the country's livestock GDP, generating nearly 717,434 direct employments (14). In Colombia, there are legislation and policies about price incentives for raw milk quality according to total solid and bacterial contents (CFU, colony forming units), but there are neither penalties nor economic incentives with low or high somatic cell count (SCC) in milk. Some pasteurization plants pay incentives for low SCC in bulk tank milk.

Previous studies on bovine mastitis in Colombia focused on the microbiological side of the problem, using CMT as the diagnostic tool and bacteriological culture to confirm the identity of the pathogen. In a longitudinal study of ten herds in the Bogota Plateau, 47% of the cows presented SCM (25% of quarters), and the predominant bacterium was *Streptococcus agalactiae* (15). In small-scale production systems in eastern Antioquia, 12.3% of the quarters were positive, *S. agalactiae* being the most frequently isolated organism (16). A more recent study of intensive production systems at the Bogota Plateau found 34% of the quarter to be positive for SCM, with 29% of the isolates being *Staphylococcus aureus*, while *Streptococcus agalactiae* was isolated in 6.8% of the samples (17).

During 2014–2016, the University of La Salle and FEDEGAN (National Federation of Livestock owners) executed a research project that aimed to generate epidemiological information on mastitis and determine the economic impact of bovine mastitis on farms located in the Bogota Plateau. The overall objective of the study was to provide epidemiologically based information on the importance and impact of SCM on farms in the municipality of Zipaquira, determining the behavior and perception of producers regarding the control and prevention of the disease, to establish the potential benefit of control alternatives and improve decision-making in that matter. This paper presents results of the financial assessment of the impact of SCM at a farm level in the region and their relationships with farm practices. Thus, the objectives of the study were 1) to determine the perception of farmers about SCM on their farms, 2) to assess the financial impacts of SCM on farms with different sizes, and 3) to assess costs and effectiveness of different control methods for SCM.

MATERIALS AND METHODS

Description of Study Region

This study was based on the field data collected during the research project entitled "Epidemiological and economic components as a basis for decision-making in the control of bovine mastitis in cattle farms in Zipaquira (Cundinamarca)." The project was funded by the University of La Salle and FEDEGAN, in collaboration with the committee of livestock producers of "Area Five" and the Inter-American Institute for Cooperation on Agriculture (IICA). The sanitary "Area Five" for foot and mouth disease vaccination encompasses 13 municipalities centered in Zipaquira in the Bogota Plateau at an altitude of 2,650 meters above sea level (m.a.s.l). Cattle population in the Bogota Plateau is about 140,000 cattle and 7,751 farms, while the Area Five (study area) population contains 16,598 cattle and 365 farms (**Table 1**).

Data Collection

Data were collected in a participatory workshop in Area Five and through both a cross-sectional epidemiological study of the prevalence of SCM and a questionnaire survey among producers of mastitis management practices (18–21).

TABLE 1 | Cross sectional survey, sampling procedure (assumes 95% CI and 10% accepted error) based on the population of the study area.

Farm strata	Number of cows by farm in the stratum	Number of Farms	Number of bovine heads	Number of cows	Average cows per farm	Number of sampled farms	Number of sampled cows per farm	Number of sampled cows per stratum
Small	10–25	188	3,101	2,171	12	28	9	230
Medium	26–100	139	6,717	4,702	34	21	18	372
Large	>100	38	6,780	4,746	125	6	28	168
Total		365	16,598	11,619	–	55	–	770

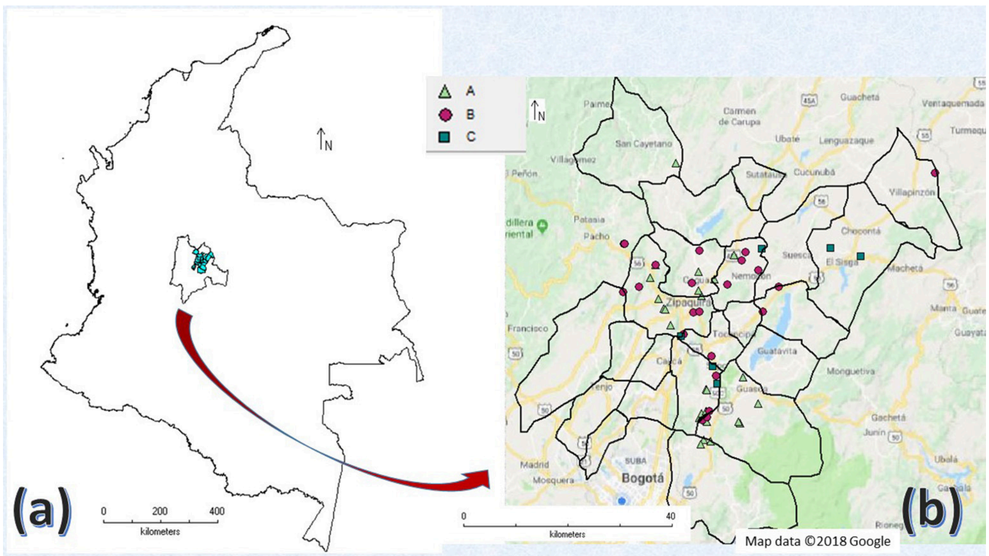

FIGURE 1 | **(a)** Area of survey location: Area Five of the Bogota plateau at Colombia and Cundinamarca department. **(b)** Farm locations at survey area discriminated by strata: A, Small; B, Medium; C, Large. (Maps were prepared using the DIVA-GIS software and geographic images from Google maps).

Participatory Epidemiology Workshop

The Area Five committee invited regional cattle producers with a total participation of 55 producers. During the workshop, they were asked to answer two questions: First, if mastitis is a problem, please describe what do you think are the main effects of this condition? Second, what actions do you implement to prevent and control mastitis in your farm? Producers wrote up their answers on cards, using one card per answer. Cards were posted on a wall in order to be discussed among participants. Cards were kept, and results were discussed at the workshop with the participants (18).

Cross-Sectional Study

A prevalence study of SCM was conducted in the area during the first semester of 2015. Farms were stratified according to the size of the production system (number of animals per farm) based on the number of farms in the study area registered by FEDEGAN (**Table 1**). Sample size of farms in each stratum was calculated by applying a probabilistic model for the estimation of frequencies (22), using the WinEpi software[1], assuming the presence of SCM in 80% of the farms, as shown in previous studies in the country (15–17), an accepted error of 10%, and a confidence level of 95%. Therefore, a sample of 55 farms was established and assigned to the strata according to the sampling fraction and the number of farms per strata (**Table 1**). In addition, farms were selected based on the producer's willingness to participate in the study. **Figure 1** shows the geographical location of the sampled farms in the study area.

The cattle sample size per farm was established using a probabilistic model, assuming SCM prevalence of 10% within the farm, an accepted error of 10%, and a confidence level of 95%. **Table 1** indicates the number of sampled animals at each farm by stratum. At herd level, sampled cows were selected at random from milking cow lists.

From each cow, an aseptic sample of milk was collected from each quarter at the milking parlor in the morning (23). Each milk sample was analyzed for SCC using the Porta SCC® system (24). Individual quarter samples showing an SCC higher than 250 × 10^3 cells/ml were considered positive for SCM. In addition, a cow was considered as "positive" if it had at least one positive quarter. A sample was considered as having "high SCC" when the count exceeded 1,000 x 10^3 cells/ml. In the results, each quarter was categorized as negative (<250 × 10^3 cells/ml), or positive to SCM: low SCC (between 250–1,000 × 10^3 cells/ml), or high

[1] http://www.winepi.net

SCC (>1,000 × 10^3 cells). Additionally, the lost quarters were counted and registered. Positive samples were cultured in blood agar and MacConkey medium, following the protocol of Sears and McCartie (23). A bulk tank sample was also collected at each farm, and SCC and bacteriological analysis were conducted.

The protocol of the study was approved by the Ethics Committee of the program of Veterinary Medicine of the Faculty of Agricultural Sciences of Universidad de La Salle, Bogota and the Research Vice-rectory of Universidad de La Salle. As part of the study protocol, the producers signed an informed consent.

Questionnaire Survey

A questionnaire survey was conducted in twice the number of farms initially required in the cross sectional study, having sufficient number of producers interviewed. Questionnaires were completed at all farms intended to participate in the cross sectional study, and additional questionnaires were filled out from neighboring farms and producers attending an animal live market in the region. Farms to be included were selected based on convenience and willingness to cooperate. A total of 103 questionnaires were completed, corresponding to 28% of the total farms within the study region.

The questionnaire included 80 questions divided in nine sections as follows: (a) respondent information; (b) farm general data; (c) clinical mastitis management; (d) SCM management; (e) milk production; (f) hand milking procedures; (g) mechanical milking system; (h) dry cow management; and (i) additional observations. The questionnaire was completed by an interviewer based on the answers from the owner of the farm or the person responsible for making decisions related to the milking process at the farm level. Only a fraction of the collected information was used in this study.

Data Analysis and Spreadsheet Modeling

Descriptive statistics were performed, using the Excel © (25) spreadsheet, to qualitatively sum up producer attitude and perception toward mastitis prevention and control expressed during the participatory workshop (55 participants) and questionnaire farm survey (103 participants).

From the cross-sectional study, the prevalence of SCM was calculated per farm as the number animals positive for SCM divided by total sampled animals. The confidence interval (CI) per farm was calculated using the disease measurement module of WinEpi (for calculation of prevalence from a sample), using a known population size and a 95% confidence level, taking into account positive animals to SCM, total sampled animals, and total number of cows present in each farm. For the calculation of prevalence and CI at the strata and regional levels, data was processed using the two-stage prevalence survey analysis tool of Ausvet epitools®[2]. Following the same approach, the prevalence of SCM in cows at the strata and regional levels was estimated by accounting for positive animals, sampled animals, and total population from FEDEGAN's records to strata and region. Differences in prevalence by strata were established by using the chi square test (25). Finally, the average farm prevalence per stratum and the range of values were calculated from individual farm prevalence calculations. The prevalence of farms having at least one cow with SCM was calculated from the sample size of farms and the total number of farms by strata.

Proportions of lost quarters and SCM positive quarters (both low and high SCC quarters) were calculated per farm using cross-sectional study results.

The financial impact of SCM was assessed by focusing on milk losses as the main source of direct cost (8, 26, 27). Milk losses per farm resulted in differences between daily potential milk production and reported daily production.

The potential daily production of milk per farm was estimated using the data from the cross-sectional study and a model based on a spreadsheet. From the average daily milk production recorded in the cross-sectional study for each farm, the increase in the potential production of milk was calculated, simulating the production of milk that would be reached if there were no cases of mastitis or quarters lost. The figures of losses associated with the results of the SCC test per quarter were adapted from Mungube et al. (11) and used as follows: reduction of 2% in quarters with > 250,000 cells/ml, reduction of 33% in quarters with > 1,000,000 cells/ml, and reduction of 100% in lost quarters.

The model allows the estimation of milk losses and their financial value per farm (using local milk prices at the farm level). Subsequently, the individual results were adjusted to 10 cows and a lactation duration of 305 days per year. The spreadsheet model used the following equations:

$$DPMQ = DRMQ^{*}\,(TQ/(TQ - UQE)),$$

where
$DPMQ$ = daily potential milk production per quarter
$DRMQ$ = daily recorded milk production per quarter
TQ = total quarters
UQE = unproductive quarter equivalence

The $DRMQ$ was calculated per farm from the recorded average daily production per cow divided by four.
In addition, TQ was calculated multiplying the total milking cows per farm by four.

$$UQE = TQ^{*}\,((1^{*}PLQ) + (0.02^{*}PLSQ) + (0.33^{*}PHSQ)),$$

where
PLQ = prevalence of lost quarters per farm
$PLSQ$ =: prevalence of low SCC quarters per farm (between 250–1,000 × 10^3 cells/ml)
$PHSQ$ = prevalence of high SCC quarters per farm (>1,000 × 10^3 cells/ml).

The yearly milk losses per farm were calculated using the results from the cross-sectional study and adjusted to lactation length of 305 days per milking cow year, following these equations:

$$DML = DPMQ^{*}\,UQE,$$

[2]http://epitools.ausvet.com.au/content.php?page=2StagePrevalence2.

where
DML = daily milk losses per farm.

Therefore, the model allows the estimation of the effect of SCM milk losses.

$$\%\ \text{Milk losses per farm} = YML/YPM,$$

where
YML (yearly milk losses per farm) = DML * 305
YPM = yearly potential milk production
$YPM = (DPMQ * 4) *$ milking cows * 305

Finally, the USD value of milk losses was calculated per farm using the reported price at farm. The exchange rate of $2,912 Colombian pesos per dollar was used as the official exchange rate on the date of the survey.

In order to reduce the effect of herd size on the absolute yearly milk losses, both yearly milk production losses and values were adjusted to 10 cows/year per farm using the following equation:

$$A10CML = (YML/\text{milking cows}) * 10,$$

where
$A10CML$ = adjusted milk losses 10 cows/year
Value of $A10CML$ = farm milk price * $A10CML$

Descriptive statistics (mean, minimal, and maximal values and standard error) were built for the whole study and per strata. Statistical significance of mean differences per stratum was analyzed using one-way analysis of variance (25) for both adjusted 10 cow year and farm absolute milk losses and values.

Regional losses were estimated from total YPM, YML, and its monetary value per stratum and scaling up to the region using the sampled farm proportion from the regional total, using the data from FEDEGAN statistics (**Table 1**), and regional total amounts were the added result of the strata.

The costs of the most frequent preventive measures were estimated based on the results of the questionnaire survey (n: 103) about control measures and using field market prices of both input and labor. Regional expenditure was estimated using frequency of answers at the survey and the standardized herd size with 10 cows.

In order to infer the effect of control measures on SCM and losses, an ANOVA regression model was run (25). The independent variables came from the qualitative data from the cross sectional farm questionnaire survey (n: 55) about preventive and control measures (**Table 3**), and the value of $A10CML$ was the dependent variable. Variance, inflation factors, and White and Breusch-Godfrey tests were applied for multicollinearity, heteroskedasticity, and auto correlation. Based on these test results and owing to the multicollinearity and heteroskedasticity found in the ANOVA model, a principal component analysis (PCA) was applied to the control measures (**Table 3**) in order to reduce both the number of variables to be analyzed and the variance.

Data appropriateness for the PCA was examined through the Kaiser-Meyer-Olkin (KMO) and Bartlett's test (28). Standard procedure for PCA was followed (28), starting with the identification of eigenvalues for each component, and followed by the extraction and the rotation of these eigenvalues. Finally, the proportional contribution of the variance of the data set was determined.

The proportion of the variance was defined as a linear estimate of the following form.

$$An = \alpha_n X_i + \beta_n \sum_{i=1}^{k} Y_i + \delta_n Z_i + \mu$$
$$Bn = \alpha_n X_i + \beta_n \sum_{i=1}^{k} Y_i + \delta_n Z_i + \mu$$
$$Cn = \alpha_n X_i + \beta_n \sum_{i=1}^{k} Y_i + \delta_n Z_i + \mu,$$

where
A_n, B_n, and C_n correspond to the farms in each stratum (A = small, B = medium, C = large),
α_n, β_n, and δ_n correspond to the coefficients for each of the independent variables of the model, namely:
X_i corresponds to the use or non-use of the CMT test on the farm; Y_i relates to the combination of the use of routine milking practices; Z_i describes the existence or inexistence of veterinary services, for each of the farms; and μ is the estimation error that includes the variables that were not included in the model.

Communalities or contribution to the variance of the data set were established following Kaiser's rule (variance over 1.0), and principal factors were established (28). Afterwards, a linear regression model (LRM) was run with the principal factors as independent variables and the value of $A10CML$ as a dependent variable. Similarly, the LRM was tested with the White test for heteroskedasticity and the Breusch-Godfrey serial correlation LM test.

RESULTS

Prevalence of SCM and the Associated Milk Production Losses

The cross-sectional study demonstrated that the overall individual prevalence of SCM in cows of Area Five in the Bogota Plateau was 55.2% (CI 95% = 43.1–67.3%; within farm variance = 0.195; between farm variance = 0.038). **Table 2** shows the prevalence of SCM in cows according to the farm stratum. There were differences between strata in the estimated values of the prevalence of SCM in cows using values for total cows in the region ($X^2 = 1399.6$; $p < 0.0001$). The quarter prevalence of SCM was 27.8%, 40.4%, and 14.7% for small, medium, and large farms, respectively. The proportions were different between strata ($X^2 = 146.68$; $p < 0.0001$). At the farm level, only one out of the 55 farms had no cows with SCM; this was a small farm (19).

Prevalence of SCM was calculated for each of the farms sampled in the study, and the average value and range by stratum is presented in the third column of **Table 2**. In addition, CI 95% for each farm was also calculated (data not shown).

Table 2 shows the average of percentage of estimated milk production losses and its range per stratum. In small farms, the

TABLE 2 | Prevalence of SCM and milk losses in farms per stratum in the Bogota plateau.

Strata (N° cows)	Stratum % prevalence of SCM♦ (95% CI)	Average cow SCM prevalence of farms by stratum (range)	Average milk loss due to SCM (%)	% Milk loss due to SCM (range)
Small (10–25)	55.6 (41.5–69.7)	55.5 (0–100)	3.97	0–12.80
Medium (26–100)	74.3 (62.8–85.8)	42.5 (22.5–64.3)	6.14	1.26–13.53
Large (>100)	36.0 (27.5–44.5)	35.1 (25.0–50.0)	3.57	1.69–5.53

♦*Correspond to cows having a quarter with SCC > 250 × 10^3 cells /ml.*
Stratum prevalence calculated using the two stage prevalence module of Epitools (SRS-stratified), using information of total population of sampled farms and total numbers of farms and animals by strata.

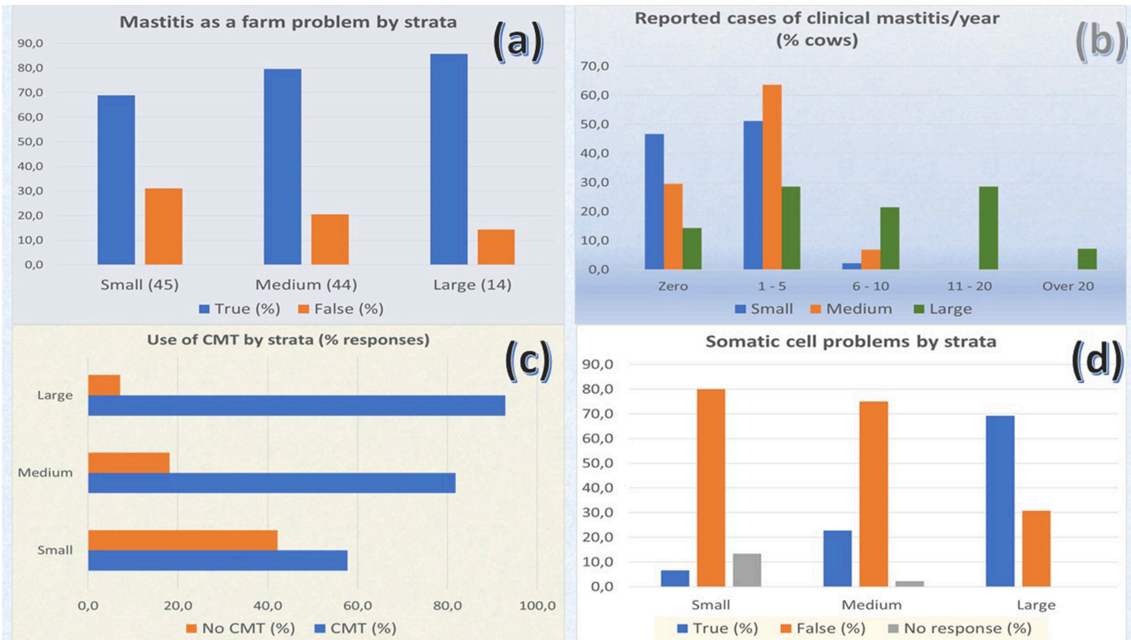

FIGURE 2 | Producer perceptions about mastitis from questionnaire survey (n:103). Frequency of percentage of answers by farm strata **(a)** Mastitis as a problem in their farms. **(b)** Occurrence of clinical mastitis. **(c)** Use of CMT at farm. **(d)** Buyers complaining about SCC in milk.

percentage of estimated milk production losses due to SCM per farm fluctuated from 0% to 12.8%, but a higher percentage of losses was observed in the medium sized farms, ranging from 1.3% to 13.5%. High dispersion of percentage of losses among farms was found irrespective of the stratum, while the scattering of values was less extended in the large farms.

Disease Perception and Control Prevention Measures

According to the questionnaire survey (n = 103), mastitis was considered a problem by 68.9%, 79.5%, and 85.7% of the producers in small, medium, and large farms, respectively (**Figure 2a**); however, no significant differences were found in the proportions between strata ($X^2 = 2.254$; $p = 0.324$). Despite the importance of the disease, producers reported a relatively low occurrence of cases of clinical mastitis per farm/year (**Figure 2b**).

Based on the participatory workshop ($n = 55$), producers were concerned about mastitis because of lower milk production (45 responses), animal health issues (18 replies), low milk quality (18 responses), public health concerns (12 responses), animal welfare (2 responses), increase in the rate of animal culling (3 responses), and other issues (4 responses).

According to the results of the questionnaire survey, producers appear not to be completely aware of the extent and impact of SCM on their production systems. In all strata, only 76% of the producers indicated SCM as a problem in their farms. However, CMT was a test routinely used for SCM detection at the farm level (**Figure 2c**). Large farms (92.9%) used CMT significantly more frequently than medium (82.9%) and small farms (58.1%) ($X^2 = 8.617$; $p = 0.0135$) (n: 103).

Upon the question of whether producers have had any complaints about the SCC in the bulk tank from milk buyers, either middlemen or pasteurization plants, 6.7%, 22.7%, and

TABLE 3 | Number (percentage) and frequency of use of preventive measures for subclinical mastitis in farms participating in the cross-sectional study, arranged by strata (n: 55).

Preventive measure	Small	Medium	Large	X^2 yates correction (*p*)
CMT	15 (54%)	15 (71%)	6 (100%)	3.206 (0.201)
Washing udder	21 (75%)	15 (71%)	1 (17%)	5.349 (0.069)
Drying udder	21 (75%)	16 (76%)	3 (50%)	0.642 (0.725)
Sealing teats	17 (61%)	18(86%)	6 (100%)	3.923 (0.141)
Dry cow treatment	18 (64%)	15 (71%)	6 (100%)	1.606 (0.448)
Cleaning milk canteens	20 (71%)	19 (90%)	4 (67%)	1.651 (0.438)
Mechanical milking system	15 (54%)	21 (100%)	6 (100%)	12.88 (0.0016)
Veterinary services	20 (71%)	21 (100%)	6 (100%)	6.061 (0.048)
Total farms	28	21	6	

TABLE 4 | Descriptive statistics of yearly financial losses associated with SCM adjusted to 10 cows per farm per year stratum (US$).

Farm strata	*N*	Mean	Min	Max	SE♣
Small	28	572.3	0	3397.6	151.1
Medium	21	936.0	98.4	4601.0	174.5
Large	6	396.1	214.4	588.2	326.4

♣*SE, Standard Error.*

64.3% of the producers from small, medium, and large farms, respectively, reported having problems regarding SCC with milk buyers ($X^2 = 18.683$; $p < 0.01$) (n: 103). **Figure 2d**.

The cross-sectional survey also indicated that, irrespective of the stratum, most of the producers tend to follow and apply a milking routine directed to reduce the impact of the disease (**Table 3**). Small producers used less mechanical milking systems and veterinary services than medium and large producers ($p < 0.01$). Medium and large producers exclusively used mechanical milking systems (100%).

Financial Losses and Effects of Preventive Measures

The estimated financial milk losses due to SCM per farm were adjusted to 10-cow herd per farm per year to allow comparisons between strata (**Table 4**). The mean of financial milk losses (value of A10CML) per farm associated with the presence of SCM were US$ 692; the range of losses was wide in small and medium farm strata, and no differences were detected across strata ($F = 1.703$; $p = 0.192$).

Economic losses in the region were estimated for each stratum (**Table 5**). The economic impact of SCM due to milk losses in Area Five (11,619 cows) was estimated to be about US$800.000/year and $70.3 per cow/year. Despite the fact that small and large farm strata have higher region's share of farms and cows, respectively, the medium stratum contributes to the highest share of both milk and economic losses due to SCM.

TABLE 5 | Regional and strata losses estimation per year, calculated for each stratum in Area Five, Bogota Plateau.

Factor	Regional level	Proportion into strata		
		Small (%)	Medium (%)	Large (%)
Farms	365	52	38	10
Cows	11,619	19	40	41
Estimated milk production (L)	43,714,447.8	19	47	34
Estimated milk losses due to SCM (L)	2,382,135.4	18	62	20
Estimated financial milk losses due to SCM (US$)	$816,361.5	17	62	21

TABLE 6 | Cost estimation (US $) of a single treatment of cows at drying off, calculated for the two veterinary drugs of more frequent use in the region and calculated regional cost of the conduct.

Product	Quantity/cow	Cost lactation/cow	Total × 10 cows/year♦	
Secamil®	4 syringes	$10.9	$113.1	
Bovisec®	4 syringes	$6.2	$65.9	
Manpower	20 min	$0.4		
REGIONAL ESTIMATION				
Strata	**Cows/region**	**Frequency of the conduct (% farms)**	**Lower cost**	**Higher cost**
Small	2,171	64	$9,156.4	$15,714.6
Medium	4,702	71	$22,000.2	$37,757.5
Large	4,746	100	$31,276.1	$53,677.3
Total	11,619		$62,432.7	$107,149.4

♦*Includes manpower costs.*

TABLE 7 | Cost estimation of a milking preventive routine using diluted iodine or a commercial product for sealing the udder (US $).

Procedure	Product	Quantity/cow	Total cost/two milkings a day/10 cows/30 days
Washing	Water	4 liters	$ 0.04
Drying off	Gazette paper	Two sheets	$ 0.93
Sealing	Iodine	10 ml	$ 0.21
	Sellodine®	10 ml	$ 19.57
Personnel	Salary	3 min/milking (preventive routine)	$ 37.09
Total	Iodine		$ 38.27
	Sellodine®		$ 57.63

Costs associated with the most frequent preventive and control measures for SCM reported on the questionnaire survey are shown in **Tables 6**, **7**. Dry cow treatments were applied overall

TABLE 8 | Regression ANOVA model of financial losses (adjusted to 10 cows/year) for preventive measures of mastitis (n: 55).

Source♦	Value	Error	*t*	*p*♣	Low CI 95%	High CI 95%	Uncentered VIF♠
Constant	234.81	716.58	0.328	0.745	−1208.5	1678.1	43.141
CMT	−338.12	251.3	−1.346	0.185	−844.3	168.0	3.537
Washing udder	−27.85	312.35	−0.089	0.929	−656.9	601.3	5.616
Drying udder	208.14	340.31	0.612	0.544	−477.3	893.6	7.207
Sealing teats	−266.85	308.60	−0.865	0.392	−888.4	354.7	6.223
Dry cow treatment	−370.57	260.81	−1.421	0.162	−895.9	154.7	4.233
Cleaning milk canteens	121.83	453.79	0.268	0.790	−792.2	1035.8	16.019
Mechanical milking system	723.25	314.58	2.299	0.026*	89.7	1356.9	6.466
Veterinary services	378.84	522.59	0.725	0.472	−673.7	1431.4	21.669

♦ *Dependent variable: Adjusted loss (US $) to 10 cows/year.*
♣ **Indicates a significant coefficient (p< 0.05).*
♠ *VIF, Variance Inflation Factors; VIF> 5 - <10 indicates moderate collinearity and VIF > 10 indicates severe collinearity.*

TABLE 9 | Total variance explained, extraction method: principal component analysis.

C♦	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	$\%S^2$	$\Sigma\ \%S^2$	Total	$\%S^2$	$\Sigma\ \%S^2$	Total	$\%S^2$	$\Sigma\ \%S^2$
1	1.985	24.82	24.82	1.985	24.82	24.82	1.737	21.71	21.71
2	1.742	21.77	46.59	1.742	21.77	46.59	1.686	21.08	42.79
3	1.090	13.62	60.21	1.090	13.62	60.21	1.393	17.42	60.21
4	0.887	11.09	71.29						
5	0.796	9.95	81.24						
6	0.698	8.72	89.96						
7	0.502	6.27	96.23						
8	0.301	3.77	100.00						

♦ *C, Component of variance—Management factors.*

by 71% of the producers and included mainly two antibiotic choices: a mixture of cloxacillin 7% and ampicillin 3.5%[3] and a combination of spiramycin and neomycin 5 g[4]. At the regional level, the costs associated with dry cow treatment varied from US $62,433 to US $107,149 (**Table 6**). Similarly, the costs associated with preventive milking routine practices depended on the type of sealant used (diluted iodine or a commercial product) and personnel (**Table 7**). On the other hand, the cost of pre-milking preparation of udders, locally referred to as "the milking routine," depends mainly on labor costs and could rise to $191–288/month for a herd of 50 cows.

The multiple ANOVA regression model used to predict financial losses from the use of disease management measures demonstrated that none of the preventive practices were individually associated with financial losses by SCM ($F = 1.255$; $p = 0.291$), although the use of the mechanical milking system had a significant effect on the model ($t = 2.299$; $p = 0.026$) (**Table 8**). Thus, a single regression model was performed to predict losses from the use of mechanical milking systems. This effect was nearly significant ($F = 3.368$; $p = 0.072$) indicating that this factor could be related with higher losses. The ANOVA model expost tests demonstrated that variances were heteroskedastic according to the White test ($F = 4.04$; $p = 0.0002$) and the absence of error autocorrelation according to the Breusch–Godfrey test ($F = 1.057$; $p = 0.31$). The uncentered variance inflation factors (VIF) shown in **Table 8** revealed that only CMT use and dry cow treatment were not linearly associated (VIF value < 5.0). As a consequence, the coefficients, although determined, show relatively high standard errors (29).

In addition to these ANOVA model expost tests results, the PCA was conducted in order to find ways of reducing multicolineality and heteroskedacity. The KMO measure of sampling adequacy was 0.529, which was considered acceptable, being higher than 0.504 (28). The values for the Bartlett sphericity test were significant ($X^2 = 62.913$; d.f. = 28; $p = 0.001$) (28). Additionally, sequential process of PCA was followed, to group preventive measures into a reduced set of three variables, which are uncorrelated with each other and accounted for decreasing proportions of the total variance of the original variables using SPSS statistics 22® (28, 29).

The PCA of prevention control measures showed relevance of three first factors (**Table 9**). The eigenvalues associated with each component (factor) before extraction, after extraction, and after rotation identified eight linear components, of which the first three explained 60% of the data variance. These three factors followed Kaiser's rule (28), and the variance shared among them is shown in **Table 9**. **Table 10** shows the communalities before

[3]Secamil®; Virbac Colombia Ltd. Bogota, Colombia.
[4]Bovisec®; Genfar, S.A. Bogota, Colombia.

TABLE 10 | Communalities.

Variables	Initial	Extraction
CMT	1.000	0.447
Cleaning udder	1.000	0.755
Drying udder	1.000	0.784
Sealing teats	1.000	0.644
Dry cow treatment	1.000	0.512
Cleaning milk canteens	1.000	0.470
Mechanical milking system	1.000	0.676
Veterinary services	1.000	0.530

Extraction method: Principal component analysis.

TABLE 11 | Rotated (Varimax) component matrix.

	Loading factors scores		
Variables	**1**	**2**	**3**
CMT	0.022	0.133	**0.845**
Cleaning udder	**0.984**	0.016	0.000
Drying udder	**0.991**	0.008	0.000
Sealing teats	0.001	**0.985**	0.014
Dry cow treatment	0.000	0.000	**1.000**
Cleaning milk canteens	0.018	0.004	**0.978**
Mechanical milking system	0.081	**0.867**	0.052
Veterinary services	0.272	**0.727**	0.001

Factor loading—three factors.
Extraction method: Principal component analysis.
Rotation method: varimax with Kaiser Normalization.
Bold indicated factors scores have values over 0.400 and identify interventions that contributed to the matrix.

and after extraction and the contribution of each intervention to the shared variance of the group. The orthogonal rotation of factors, following Varimax approach, identified the factor loading and the interventions (bold) that belong to each of the three factors (**Table 11**) (30).

The regression model of adjusted financial losses depending on the three factors is shown as follows:

Value of A10CML = 695.5 + 20.8 (Factor1) +163.6 (Factor2) - 191.3 (Factor3).

The t values and the corresponding probabilities for the factors were as follows: F1 ($t = 0.189$; $p = 0.851$), F2 ($t = 1.489$; $p = 0.143$), and F3 ($t = 1.741$; $p = 0.088$) and the regression $R^2 = 0.096$.

The model confidence is appropriate (White test: $F = 0.429$; $p = 0.9126$), and errors are not correlated according to the Breusch–Godfrey test ($F = 0.172$; $p = 0.678$).

DISCUSSION

Financial Losses

The methodological approach used in this study allowed us to estimate the prevalence of SCM and corroborate its relevance as an invisible problem that can cause financial losses to producers through the reduction of milk production (1, 3, 4, 12, 30). It is remarked that although epidemiological design was intended for a fully probabilistic sampling, as explained previously, field conditions led the authors to include farms following producer's willingness, resulting in a convenience sampling. However, it is considered that the sample is representative of the regional dairy, since a proportional number of farms of each stratum was included, according to the sampling fraction. Lack of data on variables such as intervention costs and performance prevented us from estimating other financial losses associated with SCM. Economic models that estimate milk losses caused by mastitis at both regional and local levels can be useful for implementing decision support systems that reduce the impact of the disease. In our study, the financial impact of SCM varied among farms irrespective of the stratum. Standardized adjusted yearly (305 days lactation length) milk losses for 10 cows/farm allowed comparing farms irrespective of the stratum and provided a regional picture. Therefore, there were no statistical differences in the values of A10CML between strata, contrasting with the prevalence of SCM in cows.

Nevertheless, financial losses were higher in the medium-sized farm strata, but variability, expressed by the SE, is high in all strata (**Table 4**). In general, it seems that large farms are more homogeneous in their management of SCM, and have lower financial losses despite productivity and better farm prices. Absolute farm values of both milk and financial losses depend on farm productivity, size, and market milk price.

Regional financial losses are high. They correspond to the reduction of regional milk supply, but individual farm losses are beyond the scope of the results of this research as individual production costs and gross margins were not calculated (1, 9). Despite the lack of information to calculate farm gross margin, it is assumed that measures to avoid milk losses will increase returns of producers to production costs, because the disease limits their efficiency and, therefore, the profitability (31). The main source of both losses and improvement opportunities is the farm. Therefore, the producer's decision-making is crucial, and further research is recommended to study the same.

Based on our findings, there is a larger room for improvement on the medium farm stratum. Despite such a regional financial impact, it seems like there is no incentive for the small farm producers to adopt changes, as the absolute value of estimated milk losses is low. Absence of any price incentive associated with SCC reinforces the lack of interest from producers to use diagnosis or implement control methods for SCM (32–34). Estimation of the financial impact could be used to advocate for the implementation of prevention methods that reduce the impact of SCM in Colombian dairies.

SCM Management

Although the advocacy of prevention measures by the use of economic impact assessments is quite important, the intervention efficiency is a cornerstone of economics in animal health (26, 33). Both the cross-sectional and questionnaire surveys indicated that most of the producers tend to follow and apply mastitis control management practices irrespective of the stratum. The study does not allow the evaluation of effectiveness or performance of specific prevention measures as no individual appraisal or follow-up measure was performed. The weak statistical association between preventive measures and milk economic losses due to SCM encourage us to conduct further research or provide a better understanding of SCM management (8–10, 34) through in-depth research on intervention performance, operational appraisals, and evaluation of intervention effectiveness (intervention cost vs. avoided losses).

Moreover, the high range of of the values of milk loss among farms and strata prevent any generalization in terms of efficiency and effectiveness of preventive measures for SCM implemented in each stratum. Therefore, the ANOVA expost tests, which result in multicollinearity and heteroskedacity, sustained the boundaries of this approach and the potentiality of the PCA (28, 29, 35–37). The PCA grouped measures into three components (factors). The first factor was related to the basic practices of milking hygiene. The second factor included activities that could be described as higher levels of hygiene and veterinary advice. The third factor was associated with activities related to diagnosis (CMT) and treatment of the dry cow as medical interventions. Additive effects of interventions of these factors would provide insights on how interventions work together, irrespective of measures of the individual effect of which significance was not found.

The estimation of intervention costs of the most common preventive measures indicates that the investments of producers against the disease are relevant considering the financial losses due to SCM. The intervention cost evaluation per farm was beyond the aims of this paper; therefore, a better understanding of intervention and its effect on the reduction of losses is needed so that the decision-making processes can be improved (3, 9, 34).

The value of SCC per quarter as predictor of losses and potential indicator of intervention effectiveness was demonstrated. At the field level in Colombia, the CMT is much more suitable than the Porta SCC® system because of test availability and costs. The CMT was used more frequently in the stratum of large farms, but it is necessary to understand the limitation of this test. Here, a result of grade 1 (slightly positive) corresponds to SCC between 400–1200 $\times 10^3$ cells/ml (23), which implies that this test could not detect quarters affected with SCM but that do not have a high SCC.

A phenomenon that appears to occur in the region is that the SCC requirements of the private pasteurization plants could be favoring a greater attention to SCM in large farms; for this reason, the producers in this stratum are trying to reduce the incidence of the disease and, therefore, its economic impact. In other strata, incentives are not present as they are used to selling their milk through informal market channels. Some pasteurization plants have established some price incentives for producers with low SCC. Therefore, producer's committees and pasteurization plants are providing technical advice and training on mastitis diagnosis management. Nevertheless, there are a lot of middlemen buying raw milk at farms who do not provide any service or incentive to improve milk quality. The government has set rules toward price incentives for raw milk quality according to the total solid content and CFU (<175,000–300,000) differentiating standards for specialized dairy and dual-purpose production[5]. These regulations do not include any aspect regarding SCC. This contrasts the rules in other countries such as the USA where the SCC for bulk tank milk grade A is 750 $\times 10^3$ cells/ml (32).

Results of this study and microbiological studies in milking areas of the country indicated that the most prevalent etiological agents of SCM are contagious organisms (19–21, 23). It would be expected that any intervention measure is based on an accurate diagnosis, however, the price of the diagnostic test is prohibitive. It is estimated that the price of the diagnostic test per quarter is equivalent to 25 liters of milk at farm price. The design of the prevention measures that excluded diagnosis could explain the lack of effectiveness of the preventive program shown above.

In this research, veterinary service is used and advice is apparently followed; however, a larger improvement room is feasible for both SCM detection and its management where high direct financial losses were found at both regional and farm levels. This apparent need for veterinary services in the dairy sector contrasts the low overall demand for veterinary services found in cattle production in Colombia (35). Further research on the assessment of the economic impact of SCM and effectiveness of intervention measures would improve our understanding of the disease (26, 27, 35). A major involvement of producers could also enhance their perception about the problem of SCM (9, 34, 37).

AUTHOR CONTRIBUTIONS

CM: data management; econometric analysis: variance analysis, principal component analysis; EB: lead epidemiological data analysis and interpretation; leader of the field data collection and epidemiological studies; JR: lead economic analysis and modeling, paper framework, and scope; presenter of preliminary results at the ISSEAH meeting at Scotland.

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[5]Decree 616/2006 Ministry of Social Protection and Resolution 017/2012, Ministry of Agriculture.

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