PROCEEDINGS OF THE 3RD ISESSAH CONFERENCE 2019

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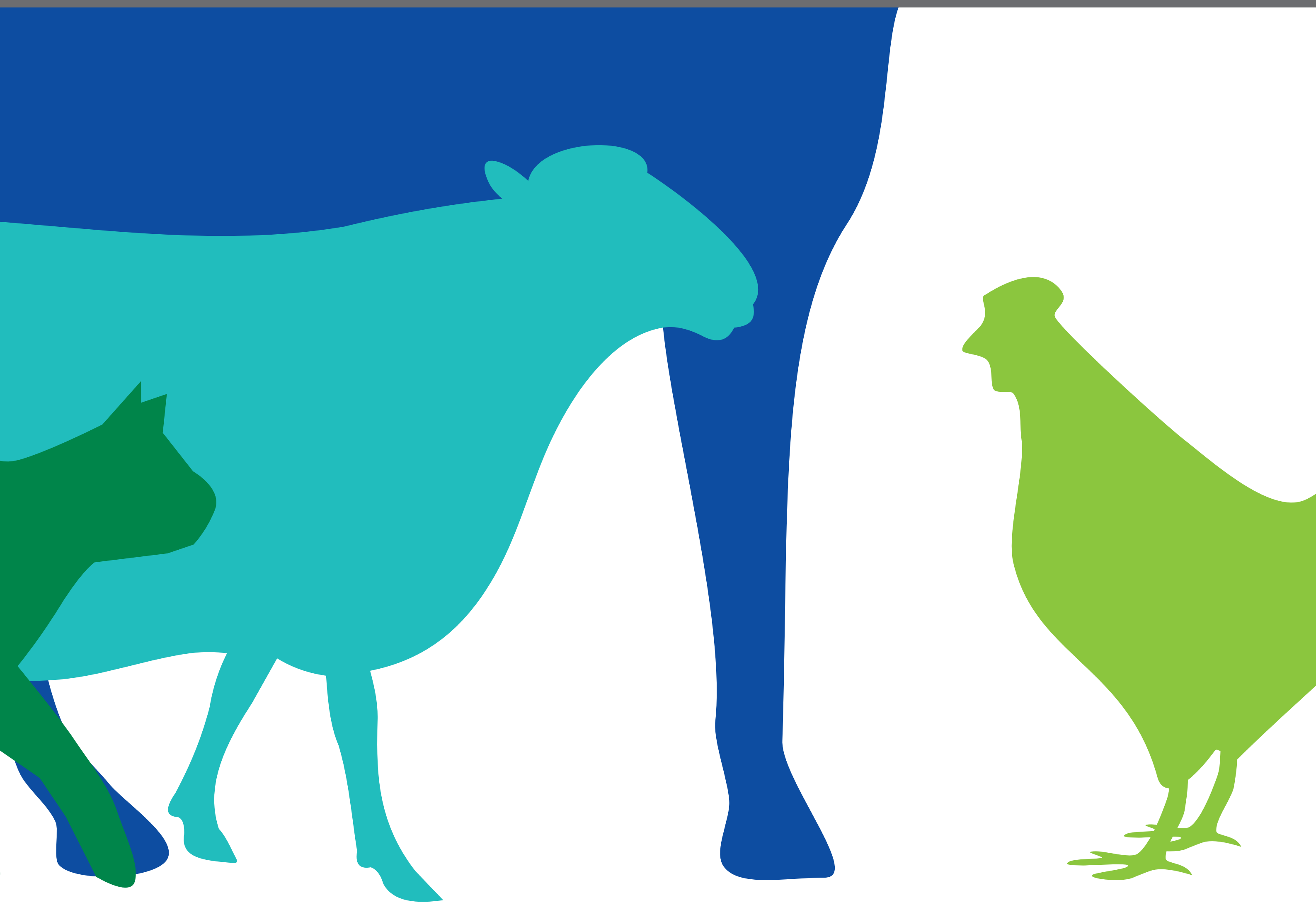

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PROCEEDINGS OF THE 3rd ISESSAH CONFERENCE 2019

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EDITORIAL
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Editorial: Proceedings of the 3rd ISESSAH Conference 2019

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Editorial on the Research Topic

Proceedings of the 3rd ISESSAH Conference 2019

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INTRODUCTION

Global animal health and welfare challenges are multifaceted and growing in complexity with the growth of human and animal populations accompanied with significant climate and environment changes. There is a realization that linkages between animal, human, and environmental health are strong and need animal and human health professionals to work together to address these growing, complex issues. This proceeding presents work that explores this discussing transboundary animal diseases [like African swine fever (ASF), foot-and-mouth disease (FMD), highly pathogenic avian influenza (HPAI)], zoonotic diseases (like rabies, liver flukes), antibiotic residues, climate change, and many more animal health and welfare issues. These papers and the ideas and work in them were presented orally and as posters at the third annual conference of the International Society for Economics and Social Sciences of Animal Health (ISESSAH) held in Atlanta, Georgia, United States in August 2019. The conference was held in conjunction with the Agricultural and Applied Economics Association's annual meeting.

The aim of the conference was to highlight interactions between human behavior and animal health, decision making impacts on biosecurity, and the One Health approach for evaluation. The proceedings of the third ISESSAH conference focus on how economics and social sciences modeling in animal health and food production can support animal and zoonotic disease prevention, mitigation, and eradication. There are 19 papers in total, including 16 original research articles, two systematic reviews, and one perspective. The three themes in this Research Topic are: (1) decision support economic modeling in animal health and food production; (2) economic assessment of infectious animal diseases and zoonoses and related control; and (3) evaluation of animal health and welfare issues.

DECISION-SUPPORT ECONOMIC MODELING IN ANIMAL HEALTH AND FOOD PRODUCTION

Kappes and Marsh estimated the protein, lipid, and carbohydrate macronutrient consumption from household food consumption in western Kenya. The authors demonstrate that livestock illness is associated with increased macronutrient shadow prices, and hence the costs of available energy consumption. Dennis et al. used two behavioral frameworks, Random Utility and Regret Minimizing, to compare demand elasticities and willingness to pay in response to an *E. coli* or antibiotic residue recall. They found the regret minimizing framework to be more powerful when assessing consumer responses. Clark et al. investigated the risks associated with producers balancing the costs of biosecurity investments and the expected benefits of those investments. Using an online experimental game that simulates biosecurity investment allocation of a pork production facility during an outbreak, they did not find any significant differences between the risk behaviors and biosecurity investments decisions of the industry professionals and the non-industry participants. Iles et al. incorporated human memory and rationality into an agent-based modeling framework to evaluate producers' decision making to vaccinate cattle in Kenya. The authors concluded that memory and rationality parameters successfully differentiated between vaccination decisions that are annual and once-for-life. de Menezes et al. adopted a Social Network Analysis and conducted an exploratory analysis of cattle movement in Brazil. They found cattle movement networks were strongly connected, suggesting a high-speed diffusion of FMD, if reintroduced. Additionally, they concluded the need for investment in animal movement, education for producers and technologies to assist in early detection, diagnosis and eradication of FMD outbreaks. Pramuwidyatama et al. used Theory of Planned Behavior to better understand the factors associated with small-scale broiler producers in Western-Java toward cleaning and disinfection, vaccination, reporting, and stamping out in the event of HPAI. The authors suggested policies should be emphasized toward preventative measures rather than control measures. Aslam et al. employed key informant interviews and a focus group discussion to characterize and map the broiler and layer production systems, values chains, and poultry disease management in Pakistan.

ECONOMIC ASSESSMENT OF INFECTIOUS ANIMAL DISEASES AND ZOONOSES AND RELATED CONTROL MEASURES

Thomann et al. assessed the profitability of porcine reproductive and respiratory syndrome vaccines in Germany. The authors found the benefits were greatest when both sows and piglets were vaccinated and when vaccination was adopted by previously non-vaccinating herds. Ozturk et al. utilized a partial budget approach to analyze the economic impacts of biannual mass vaccination vs. vaccination every 4 months for FMD in border cities in Turkey. They conclude that the more intense vaccination strategy could be more cost effective than the current biannual mass vaccination. Machado Junior et al. used a Bayesian hierarchical spatio-temporal model to determine the factors associated with farm and broiler house characteristics and management practices using data from a Brazilian integrated broiler enterprise. The authors suggested that both time and space increase the odds of isolating *Samonella* spp. from litter, as well as, the size and type of the broiler house, total housing area per farm, and the number of litter recycles. Gilbert et al. evaluated the economic impacts of coccidiosis under different efficacies on control in European intensive broiler systems. The authors concluded that the impacts of coccidiosis increased rapidly as control efficacy decreased. Niemi analyzed how ASF outbreaks impacted swine production (quantity and prices) and exports in 11 European countries using a seemingly unrelated regression. He found that new ASF cases reduced production of pork by 4% and exports by 15% in the following year after the outbreak, and 3–4% in the national pig inventory. In a perspective by Beyene et al., they provided evidence on the socioeconomic burden of rabies in dogs in Ethiopia. Shrestha et al. investigated the financial impacts of liver fluke infections with and without climate change effects on Scottish livestock farms using a linear programming model. The authors found a 12 and 6% decrease in net profit on an average dairy and beef, respectively, farm under normal disease conditions and 2- and 6-fold losses in dairy and beef, respectively, farms when climate changes effects are incorporated into the model.

EVALUATION OF ANIMAL HEALTH AND WELFARE ISSUES

Thompson et al. explored the effects violence and environmental effects along the U.S.—Mexico border on cattle fever ticks. The authors suggest the both media-reported violence and changes in weather impact the rate at which infested cattle are apprehended. Rothman-Ostrow et al. evaluated the use of Tropical Livestock Unit to measure biomass and compare that to two proposed alternatives. After analyzing the three methods using publicly available data for cattle from six sub-Saharan Africa countries, the authors highlight the difference in results between the three methods and suggest that standardizing data collection will allow for better livestock population and biomass estimates. By conducting a systematic literature review and meta-analysis, Afonso et al. estimated the frequency levels of lameness in British dairy cattle and documented the patterns of how lameness is detected and classified in research. They concluded that regardless the method that was used to measure lameness, it is high in British dairy cattle. In an article by Raboisson et al., they used a meta-analysis to look at losses due to clinical mastitis losses and identify which factors influence those effects. The average loss was estimated at €224 per case and that labor, drug, and culling costs, and treatment price had a significant impact on the losses. Using collected blood samples and surveys from herd management administrators on pig farms in Indonesia, Nurhayati et al. estimated and investigated which risk factors impacted Swine influenza virus (SIV) seropositivity status. The authors found farm-level SIV seropositive rate was 26% and the presence of animals on the farm (excluding pigs), keeping breeding sows for <2 years, being located near a poultry farm, and purchasing pigs only through collectors increased the risk of being seropositive to SIV.

CONCLUSION

The collection of 19 articles in this Research Topic from the 3rd annual ISESSAH conference provides a good read on important socioeconomic issues surrounding animal health management and welfare. It is the hope from the authors of this Editorial that ISESSAH and similar organizations will continue to bring animal health professionals together to tackle the growing complex animal health issues that we are faced in today's world, ultimately increasing societal welfare.

AUTHOR CONTRIBUTIONS

DP drafted the editorial. TM and DP had an advisory role and provided input at the designing stage of the Research Topic. TM, JR, DR, HH, and BV reviewed and revised the editorial. DP, BV, DR, HH, and JR contributed to the reviewing and editing of the papers published in the proceedings of the 3rd ISESSAH conference 2019. All authors contributed to the article and approved the submitted version.

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SYSTEMATIC REVIEW
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The Use of Meta-Analysis for the Measurement of Animal Disease Burden: Losses Due to Clinical Mastitis as an Example

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The literature contains an extensive panel of studies focusing on the costs of animal diseases. The losses of an agriculture holding can be influenced by many factors since farming is a complex system and diseases are closely interrelated. Meta-analysis can be used to detect effects (i.e., change in clinical mastitis losses here) across studies and to identify factors that may influence those effects. This includes the external validity of the published study results with regard to the input parameters and the internal validity of the study, particularly how other diseases related to the target disease were accounted for. Mixed-effect meta-regressions were performed to estimate the mean clinical mastitis losses per case across the literature and to elucidate to what extent clinical mastitis losses are influenced by (i) general factors, such as etiology; (ii) the types of losses that contribute to the total mastitis losses; and (iii) prices. In total, 82 observations from nine studies were included in the meta-analysis to assess mean clinical mastitis losses per case. The multivariate meta-regression showed that etiology significantly influenced the clinical mastitis loss per case. The mean loss was determined to be €224 per case for all published etiologies. In detail, mean losses equalled €457 and €101 per case of clinical mastitis due to gram-negative and gram-positive bacteria, respectively, and €428 and €74 per case of clinical mastitis due to *Escherichia coli* and *Staphylococcus aureus,* respectively. Additionally, the mean loss obtained depended on whether diagnostic costs and reduced feed intake in cases of mastitis were included in the clinical mastitis loss calculation. The monetary values of labor cost, drug cost and culling cost, as well as treatment price (all included), significantly influenced the clinical mastitis losses per case. All other tested moderators were not associated with mastitis losses, highlighting the need for more standardized economic studies, for both methods and ways results are presented, and suggesting that the mastitis losses assessed in the literature cannot be extrapolated (limited external validity). Although meta-analyses are useful to overview the burden of diseases across studies, their ability to summarize extensive literature with various economic assessments is limited. These limitations in loss assessments also suggest the need to focus on management strategies rather than on pure monetary estimations of disease costs, at least for production diseases at the farm level.

Keywords: clinical mastitis, economics, etiology, meta-analysis, dairy cows

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INTRODUCTION

Some reviews show large variations in the calculated impact of animal diseases, such as subclinical ketosis bovine viral diarrhea (1–3). There is increasing concerns of cost evaluation in the context of animal diseases because of difficulties in assigning disease cost to an individual disease due to the co-existence of simultaneous diseases (4). Consequently, the risk of overestimating by including the same contributors in the costs of different diseases is high (5–7). Further, key questions in disease impact evaluation is whether and how the results can be extrapolated, particularly considering the high price volatility of input and output parameters in economic assessments. Trends that focus on the whole economic strategy to manage disease rather than on the cost of disease to address this concern are increasing (5, 8). We hypothesize that meta-analysis may be an adequate approach to define how factors such as the type of incorporated losses and the associated prices may influence the value of the economic burden of the disease across the studies.

Mastitis is one of the most important diseases in dairy farms worldwide (9, 10); it is related to economic, environmental and societal stakes through losses, increased carbon and nitrogen outputs from the production process, and increased antimicrobial use (11, 12). The cost of mastitis differs across studies (1, 13, 14), particularly regarding etiology, clinical degree, types of losses included in the mastitis costs, treatment costs, level of prices, and economic assessments methods used. Mastitis is a complex disease, and its diagnosis can be clinical, bacteriologic, and cytologic. Clinical mastitis includes local and general clinical signs, and subclinical mastitis is diagnosed when no clinical signs are observed. A bacteriological diagnosis includes the identification of the etiology of mastitis and antibiotic sensitivity of the pathogen. A cytologic diagnosis is based on milk somatic cell counts (SCCs), which is a proxy generally used to measure subclinical mastitis, despite clinical mastitis lead to high SCCs.

The present work focuses on the factors that may influence losses due to animal diseases, using clinical mastitis as an example, to define whether the present state of the economics of this disease can be adapted to elucidate the (i) internal validity of the study (what is accounted for during the economic assessment) and (ii) the external validity of published study results with regard to the input parameters used. It aims to describe the usefulness of meta-analysis to evaluate which factors may influence the estimated losses due to mastitis infections in the dairy population according to the literature.

MATERIALS AND METHODS

Literature Search and Criteria for the Inclusion or Exclusion of Studies

Publications on the losses due to clinical mastitis were selected from English-language literature up to June 2019. The literature search was conducted in PubMed, Science Direct, and Google Scholar. The keywords were applied separately or in different combinations for the literature search in the three databases. Subsequently, the reference lists of the identified studies were also screened. All the studies were analyzed according to the following inclusion criteria: (i) the publication included clinical mastitis and presented results for clinical mastitis separately from subclinical mastitis if both were included; (ii) the publication included the monetary losses presented per clinical mastitis case or per year and cow; (iii) the publication results were obtained in temperate-climate countries; and (iv) the publication data was obtained after 1990 to represent the modern livestock system. No restrictions were set on the intensification level (milk production), the level of monetary losses due to clinical mastitis, or the currency used. Publications focusing only on the preventive costs of clinical mastitis and/or on specific breeds (Simmental) and/or determinist methods with no variance associated with the mean losses were excluded. In the present work, production losses and curative extra costs were eligible to be considered as clinical mastitis losses. All expressions and proxies of the variance were accepted [i.e., standard deviation (SD), standard error (SE), min-max, confidence intervals] and transformed into a unique unit (i.e., SE) to compare the results across the included studies.

The total number of identified publications and the applied two-step selection process for eligible studies, which was performed in accordance with the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analysis), are illustrated in **Figure 1**. All articles were screened in full by two reviewers (TG, DR) and eligible studies, i.e., those which met the inclusion criteria, were then reviewed in full by one reviewer (TG) in accordance with the predefined variables shown in **Table 1**. All relevant data from the eligible studies were entered into a Microsoft Excel spreadsheet (**Table S1**). A publication was further divided into different observation sets if the study considered different variables, according to **Table 1**, into account and thus published different monetary losses per animal. Consequently, the total number of publications included in the presented study was not identical to the total number of observations. The details of the four incorporated groups of variables (called moderators) are reported in **Table 1**. In brief, they refer to (A) general variables (year, etiology), (B) the type of losses (i.e., nature of the contributors of the losses) considered either included or excluded from the published raw models, (C) the monetary level of losses for each contributor (in Euros), and (D) the prices used as input parameters in the published raw models.

The clinical mastitis losses reported in the literature were standardized per case of clinical mastitis. The mastitis losses were published in different national currencies and years. A standardization to the Euro (€) and the year 2018 for each respective country was performed as follows:

$$Y\_DL_{(€;\ 2018)} = \frac{Y\_DL^{i}_{X}}{\tau_{conv^{X}(i \to €)}} * \left(\frac{I\_OCDE_{2018}}{I\_OCDE_{X}}\right) \quad (1)$$

where *Y_DL (€; 2018)* represents the mean clinical mastitis losses per animal in € in 2018, and *i* indicates the national currency

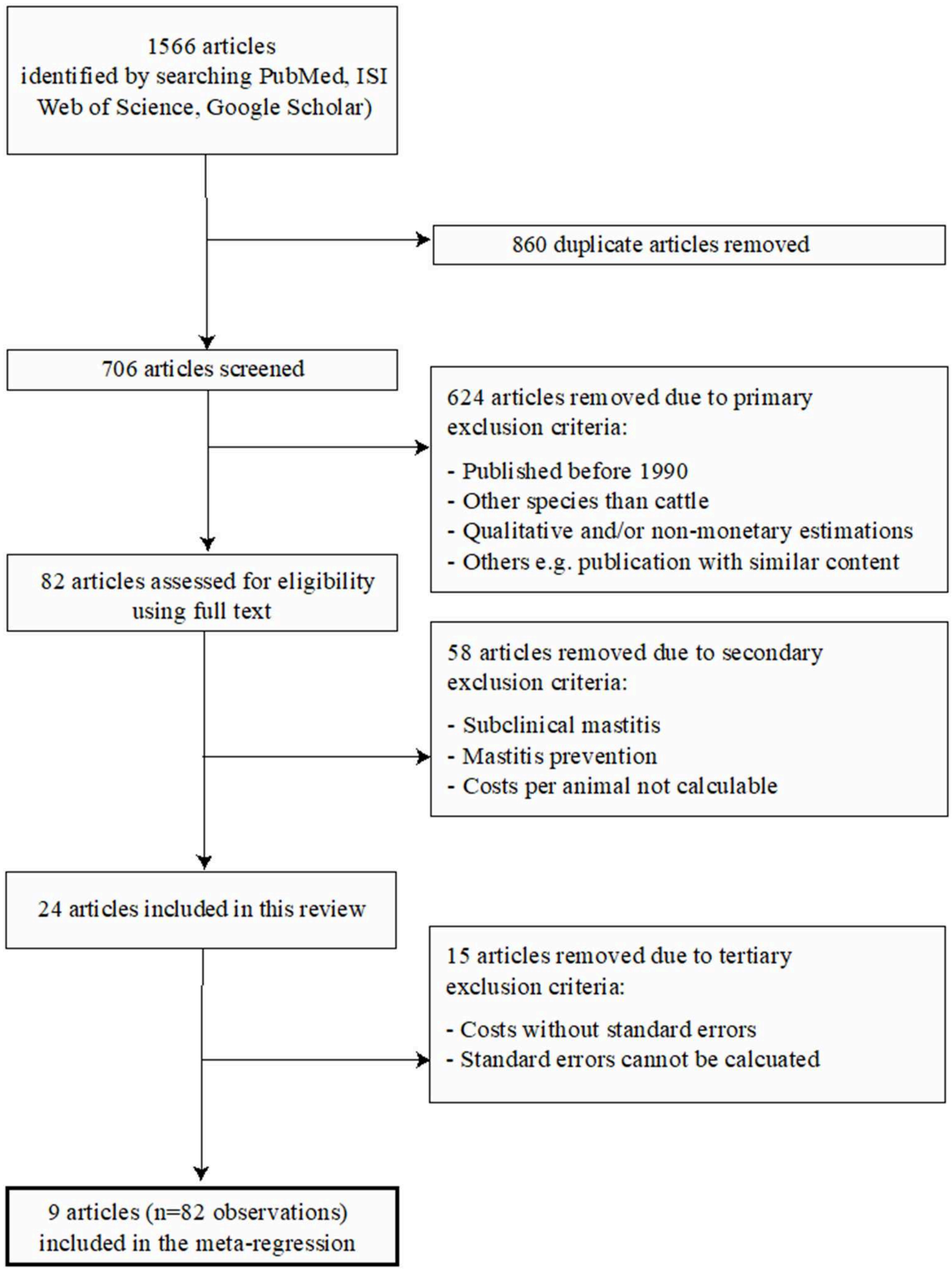

FIGURE 1 | Flow diagram of the selection process for the systematic literature review. The final regressions included eight articles, since the influential analysis has led to exclude one article.

of the respective country for which losses were determined in the year X. The nominal exchange rate ($\tau_{conv}\,X_{(i\rightarrow€)}$) was distinguished between the Eurozone (i.e., exchange rate of the national currency i into the currency € in 2002) and non-Eurozone (i.e., exchange rate of the national currency i into the currency € in the year of publication). The index I_OCDEx includes the economic annual growth rate of the respective country and incorporates the inflation rate based on the consumer price index. The same procedure of standardization to the Euro (€) and the year 2018 was applied for all monetary values in the dataset (**Table S1**).

Meta-Analysis

The meta-analyses were implemented in R (Version 3.5.1 R Foundation for Statistical Computing, Vienna, Austria) using the Metafor package (15). Random-effects models were first used to estimate the log-effect size and its 95% confidence interval (CI) and statistical significance level. The statistical

TABLE 1 | Factors selected from the systematic review and considered in the meta-regression analysis.

Moderators	Class	Number of observations	Mean (± SE) value of the clinical mastitis losses (in €)	Meta-regression set in which the data is included
(A) GENERAL				
Study type	Modeling	42	293 ± 105	1, 2, and 3
	Descriptive	40	227 ± 159	
Publication year	Numeric	82	262 ± 137	1, 2, and 3
Country	Nominal	82	262 ± 137	1, 2, and 3
Number of herds	Numeric	51	267 ± 145	1
Average herd size	Numeric	49	261 ± 146	1
Number of clinical cases	Numeric	20	291 ± 129	1
Average milk yield[a]	Numeric	35	305 ± 110	1
Parity	All	68	245 ± 144	1
	Primiparous	6	287 ± 19	
	Multiparous	8	379 ± 17	
Incidence (%)	0.12	6	287 ± 19	1
	0.20-0.24	8	379 ± 17	
	0.35	1	87	
Prevalence (%)		48	225 ± 55	1
Etiology 1	All pathogens	48	282 ± 112	1
	Gram positive	16	155 ± 68	
	Gram negative	6	477 ± 119	
	Other (no growth, two pathogens)	12	235 ± 173	
Etiology 2	All	48	282 ± 112	1
	S. aureus[e]	4	123 ± 30	
	S. coag.[e]	4	168 ± 104	
	S. spp.[f]	8	165 ± 64	
	Gram negative	6	444 ±108	
	(Other no growth, two pathogens)	12	264 ± 195	
Etiology 3	All	48	282 ± 112	1
	S. aureus[d]	4	123 ± 30	
	S. coag.[e]	4	168 ± 104	
	Streptococcus Esculine +	4	152 ± 15	
	Streptococcus Esculine -	4	178 ± 95	
	Gram negative	6	444 ± 108	
	Other (no growth, two pathogens)	12	264 ± 195	
(B) TYPE OF lOSSES: CONTRIBUTORS TO MASTITIS LOSSES (ACCOUNTED FOR OR NOT)				
Diagnosis (before treatment)[b]	No	76	261 ± 140	1
	Yes	4	281 ± 15	
Feed intake (saved if mastitis)[c]	No	46	221 ± 151	1
	Yes	36	311 ± 97	
Milk withdrawal	No	0		No
	Yes	82	262 ± 137	
Milk not produced	No	4	87 ± 17	1
	Yes	78	271 ± 134	
Veterinary cost	No	20	291 ± 129	1
	Yes	62	252 ± 139	
Drug cost	No	0		No
	Yes	82	262 ± 137	
Extra labor	No	3	87 ± 21	1
	Yes	77	268 ± 135	

(Continued)

TABLE 1 | Continued

Moderators	Class	Number of observations	Mean (± SE) value of the clinical mastitis losses (in €)	Meta-regression set in which the data is included
Culling	No	4	87 ± 17	1
	Yes	76	271 ± 134	
Extended day open	No	66	245 ± 144	1
	Yes	14	340 ±50	
Cow Mortality	No	19	175 ±74	1
	Yes	63	289 ±141	
Carcass disposal	No	19	175 ± 74	1
	Yes	63	289 ± 141	
Milk replacer used	No	32	257 ± 125	1
	Yes	48	265 ± 145	
(C) MONETARY LEVEL OF LOSSES (VALUE OF EACH CONTRIBUTOR)				
Milk withdrawal		13	261 ± 78	2
Milk not produced		24	245 ± 83	2
Veterinary cost		16	221 ± 100	2
Drug cost		24	328 ± 78	2
Extra labor		26	239 ± 87	2
Culling		25	245 ± 83	2
Extended day open		2	328 ± 61	No
Cow Mortality		3	306 ± 57	No
(D) PRICES (OF INPUT PARAMETERS OF RAW mODELS)				
Cow culled (€/kg carcass)	1.69	12	341 ± 50	3
	1.94	2	334 ±70	
Replacement heifer (€/head)	1502	12	341 ± 51	3
	1684	2	330 ± 59	
Milk (€/kg)	0.31	12	375 ± 82	3
	0.33-0.37	15	316 ± 83	
	0.41-0.49	5	366 ±62	
Feed (€/ kg) dry matter	0.16	12	345 ± 48	3
	0.18	2	307 ± 64	
Labor (€/h)	5.89-10.58	13	353 ± 112	3
	19.42-23.88	16	199 ± 64	
	28.88-30.36	14	340 ± 50	
	36.76	35	224 ±153	
Treatment (€/treatment, all included)	Numeric	32	253 ±124	3

[a] *305-days average milk production;* [b]*mastitis diagnosis before treatment;* [c]*adjustment for reduced feed intake in cases of mastitis;* [d]*Staphylococcus aureus;* [e]*coagulase negative-Staphylococcus;* [f]*Escherichia coli.*

heterogeneity between and within studies was assessed using the Cochran Q statistic and the I^2 statistic, respectively (16). For response variables with high I^2, uni- or multivariate meta-regression was then performed to explore the sources of heterogeneity. The meta-regression was conducted by screening for the moderators, as described in **Table 1**. A moderator was a variable that resulted in reduced heterogeneity when introduced in the meta-regression (i.e., factor). In the first step, the meta-regression was performed for all factors together and then separately for (A) the general factors, (B) the type of losses (i.e., contributor), (C) the monetary level of losses for each contributor, and (D) the prices used for the economic input parameters. The variable "Publication" was kept as a random effect. The inclusion of the factors in the meta-regression analysis was conducted as follows. Univariate meta-regressions were first performed to identify factors according to **Table 1** that may have had a significant association with the clinical mastitis loss per case. A reference class for each factor was chosen to allow a comparison of the effect size. Any significant factors in the univariate test were selected as a potential influencing factor for the multivariate analysis, which aimed to reduce the heterogeneity between the included studies in the meta-analysis. The τ^2 (residual heterogeneity variance) denoted the amount of heterogeneity that may not be explained through the inclusion of the factors in the meta-analysis. Publication bias was identified by performing the Egger test, a regression test for funnel plot asymmetry and inspection of the associated funnel plots (**Figure 2**). Outliers were also identified by conducting

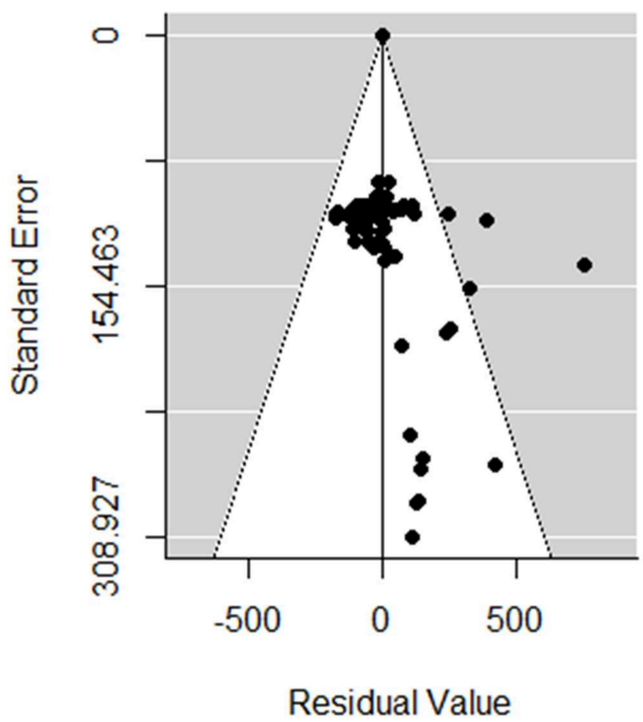

FIGURE 2 | Funnel plot of the random meta-analysis of studies, without the incorporating moderators in **Table 1**.

influential case diagnostics (i.e., DFFITS value, Cook's distances, covariance ratios, estimates of τ^2 and test statistics for (residual) heterogeneity). Because the dataset contained moderators with different numbers of missing data, three subdatasets were proposed, as described in **Table 1**, and meta-regression was performed accordingly.

RESULTS

In total, 82 observations from nine studies were included in the meta-analysis (**Table S2**). Influential case diagnostics indicated two observations and one study as sources of asymmetry. These observations were considerably higher regarding clinical mastitis loss per case (with a mean of €1,000) than other observations (with a mean ± SD of €262 ± 137) and thus highly influenced the results of the meta-regression. Consequently, two observations and one study were excluded in the presented meta-analysis. The estimated pooled effect size obtained with the random-effects model with no moderator (**Table 2**) was €195 (Se = 37, $p <$ 0.001). No publication bias was determined with the Egger test ($t = 269$, $p = 0.21$). The heterogeneity between the studies was very high ($I^2 = 99.9\%$; AIC = 99,711; Q-Test: $x^2 = 99{,}136$; df = 79; $p < 0.001$).

The meta-regression with all moderators, which was performed on the dataset including the moderators without any missing data (denoted subdataset 1 in **Table 1**), showed that mastitis losses were associated with the etiology of mastitis as well as with the inclusion diagnostic costs and feed intake decreases in cases of mastitis in the raw model (**Table 2**). The observed decrease in the heterogeneity through the inclusion of these factors was 33%. A diagnosis before treatment was associated with an extra loss of €155 per case, and the adjustment of the cost assessment by the diet saved with a reduced the loss per case by €35. The average losses of gram positive and gram negative clinical mastitis were €101 (€224–€123) and €457 (€224+€233), respectively. The losses were €74 (€224–€150), €79 (€224–€145), €121 (€224–€103) and €428 (€224+€204) for mastitis due to *Staphylococcus aureus*, coagulase-*Staphylococcus*, *Streptococcus* spp., and *Escherichia coli*, respectively (**Table 2**).

The dataset focusing on the monetary levels of losses includes 26 observations (denoted subdataset 2, see **Table 1**). All moderators summarized in the term monetary levels of losses in **Table 1** were significantly associated with the cost of mastitis, but correlation was observed between the moderators (**Table 3**), leading to the final regression proposed in **Table 2**. The marginal values of drug cost, labor cost and culling cost in clinical mastitis losses were €0.8, €2.9, and €1.04, respectively. This means, for instance, that one extra euro for the drug cost was associated with an extra clinical mastitis losses equal to €0.8.

The dataset focusing on prices of inputs included 12 to 76 observations, depending on the moderators (denoted subdataset 3, see **Table 1**). The price of treatment (all included) was associated with a marginal value in the clinical mastitis-related loss of €0.76 (Se = 0.04, $p < 0.0001$). All other moderators, including the price of milk, were not associated with the losses of clinical mastitis ($p > 0.7$ for the three classes compared to the reference class, **Table 1**).

The influential case diagnostics of the three meta-regressions shown in **Table 2** indicated outliers in the incorporated influencing factors on mastitis losses (**Figures S1–S3**). The removal of the outliers did not change the coefficients of the meta-regressions, and the results shown in **Table 2** were considered final. Final forest plots are reported in **Figures 3–5**.

DISCUSSION

The meta-regression was performed according to usual recommendations (17, 18). The final choice for the models was made considering the decrease in heterogeneity. More than one model was reported for the same outcome because the authors judged that all the models had biological significance and would be of interest to the scientific community. The multivariate models provided in **Table 2** show close coefficients compared to the univariate models, and the addition of a new moderator reduced the heterogeneity. Unfortunately, many studies did not report any estimation of the variance (determinist method) and could not be included in the present meta-regression, leading to only nine included publications, although extensive literature is available. This issue has been highlighted in a previous review (13). The present meta-analysis and the previous review (13) both highlight the high heterogeneity within the method used to assess mastitis losses, the nature of the included losses and the limits of comparing

TABLE 2 | Final factors considered in the meta-regression analysis.

Group of moderators[a]	Moderator and class	Estimate (SE)	95% CI	*P*-value
Without	Intercept	195 (37)	122/267	<0.0001
A and B: General and type of mastitis losses	Intercept	224 (43)	139/308	<0.0001
	Gram positive (ref=All)	−123 (7.3)	−108/−137	<0.0001
	Gram negative (ref=All)	233 (16.3)	201/264	<0.0001
	Other (ref=All)	−133 (7.0)	−119/−146148/161	<0.0001
	Diagnosis (ref= No)	155 (3.5)	148/161	<0.0001
	Feed intake (ref = No)	−29 (2.5)	−24/−34 139/308	<0.0001
A and B: General and type of mastitis losses [b]	Intercept	224 (43)	139/308	<0.0001
	Staphylococcus aureus (ref=All)	−150 (9)	−132/−167	<0.0001
	Staphylococcus spp. (ref=All)	−145 (11)	123/166 166166	<0.0001
	Streptococcus spp. (ref=All)	−103 (8)	−87/−118	<0.0001
	E. coli (ref=All)	204 (18)	168/239	0.0097
	Other (ref=All)	−131 (7.0)	−117/−144	<0.0001
	Diagnosis (ref= No)	155 (3.5)	148/161	<0.0001
	Feed intake (ref = No)	−29 (2.5)	−24/−34	<0.0001
C– Monetary level of losses[c]	Intercept	124 (43)	39/208	0.0039
	Labour[e]	2.9 (0.24)	2.4/3.4	<0.0001
	Drug cost[e]	0.8 (0.04)	0.72/0.87	<0.0001
	Culling[e]	1.04 (0.02)	1.00/1.08	<0.0001
D- Prices[d]	Intercept	150 (39)	73/226	<0.0001
	Treatment (all included)[f]	0.76 (0.04)	0.68/0.83	<0.0001

[a]*as defined in* ***Table 1***.
[b,c,d]*the corresponding influential case diagnostics are indicated in* ***Figures S1***, ***S2***, *and* ***S3***, *respectively.*
[e]*the moderator is a continuous variable that equals the monetary value of the contributor of the losses due to clinical mastitis. The coefficient is then expressed as the marginal value of loss (for one extra euro of the total value of the contributors "labor cost," "treatment cost," and "culling cost").*
[f]*the moderator is a continuous variable that equals the price of treatment considered in the raw model. The coefficient is then expressed as the marginal value of loss (for one extra euro of treatment price).*

TABLE 3 | Correlations (and *P*-values) of the values of the moderators in the category "monetary level of losses" (moderator group C, see **Table 1**).

	Milk not produced	Milk withdrawal	Veterinary cost	Drug cost	Extra labor	Culling
Milk withdrawal	0.92/<0.001[a]					
Veterinary cost	0.92/<0.001	0.94/<0.001				
Drug cost	−0.02/0.89	0.36/0.06	0.43/0.06			
Extra labor	0.77/<0.001	0.9/<0.001	0.85/<0.001	0.04/0.8		
Culling	0.68/<0.001	0.6/<0.001	0.53/0.005	−0.34/0.9	0.39/0.01	
Mortality	−0.2/0.38	0.32/0.26	−0.61/<0.001	0.61/0.01	0.67/0.09	0.78/0.06

[a]*Expressed as correlation value/P-value.*

or summarizing results. In spite that one aim of the present work was to adjust the estimation of clinical mastitis losses by the occurrence of other diseases, data available did not permit to do for most of the regressions since papers included in the meta-analysis only scarcely reported other diseases that may interact with mastitis. Moreover, even if many non-significant associations were found in the present study, it helps (i) to determine factors influencing mastitis losses, (ii) to quantify heterogeneity, and (iii) to highlight the concerns faced when aiming at reducing heterogeneity in the context of clinical mastitis losses.

The present study should remind the reader that focusing on the cost or loss of disease may be of limited value for some diseases, such as mastitis. The present results show that the losses of clinical mastitis were higher for gram negative mastitis than for gram positive mastitis, although opposite perception has been reported from the field. For instance, the management of gram negative mastitis is easier than gram positive mastitis, although the long-term consequences of udder contamination by gram positive are greater than those for gram negative mastitis (treatment efficacy, chronic infection). This result is in accordance with the fact that medium- or long-term SCCs arising from clinical mastitis are poorly accounted for in the present works since they are scarcely reported in the literature. Similarly, the way culling is integrated in the studies remains unclear. This result demonstrates that any economic

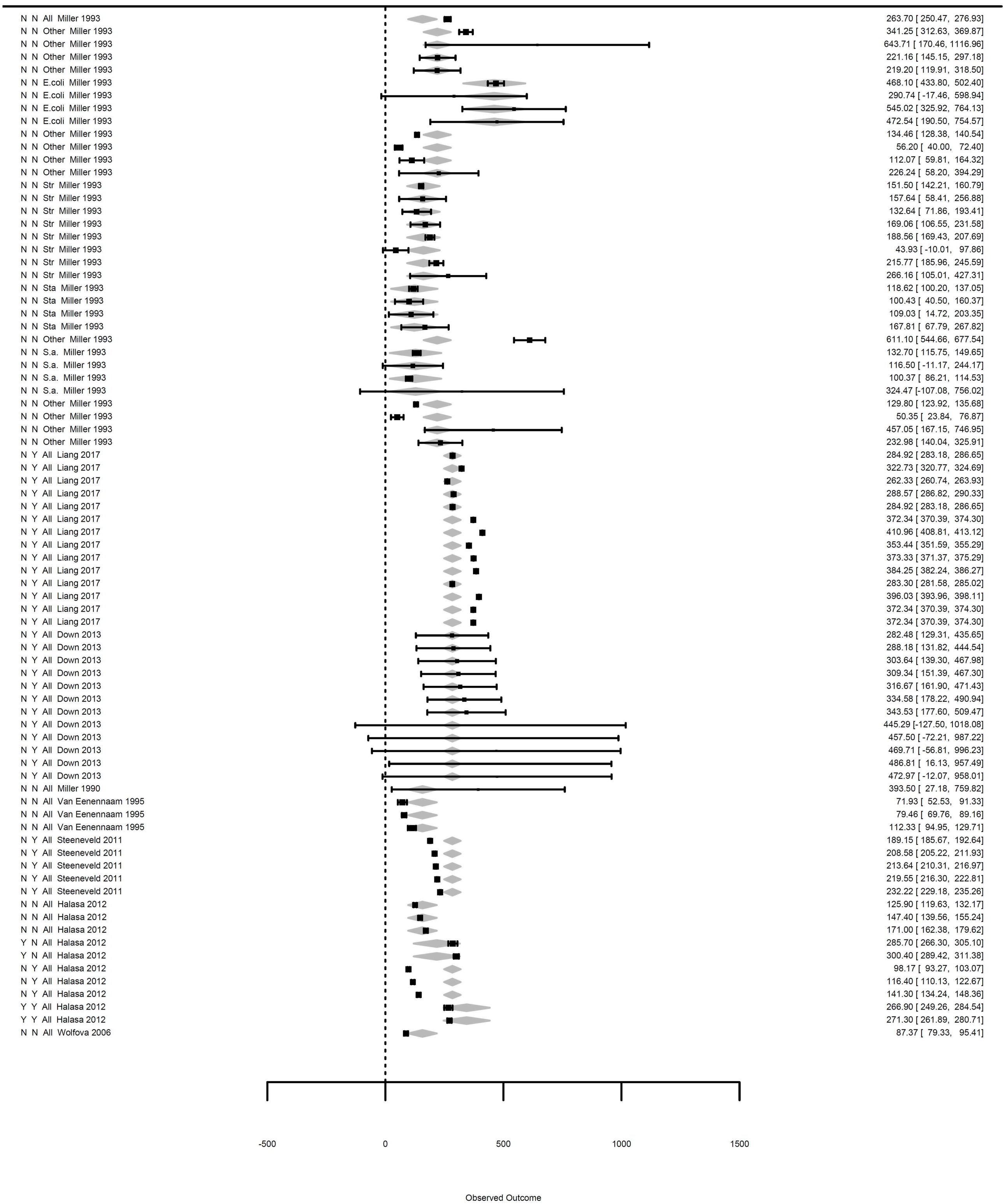

FIGURE 3 | Forest graph of the meta-regressions including moderators in groups A and B. The column on the right refers to the mean loss per case with the corresponding confidence interval (in brackets). The two single letters in the left column represent the moderators diagnosis and feed intake, as defined in **Table 1**. The moderator etiology (**Table 1**) is located to the left of the authors. The gray diamonds represent the effect size adjusted for the moderator and are included in the meta-regression.

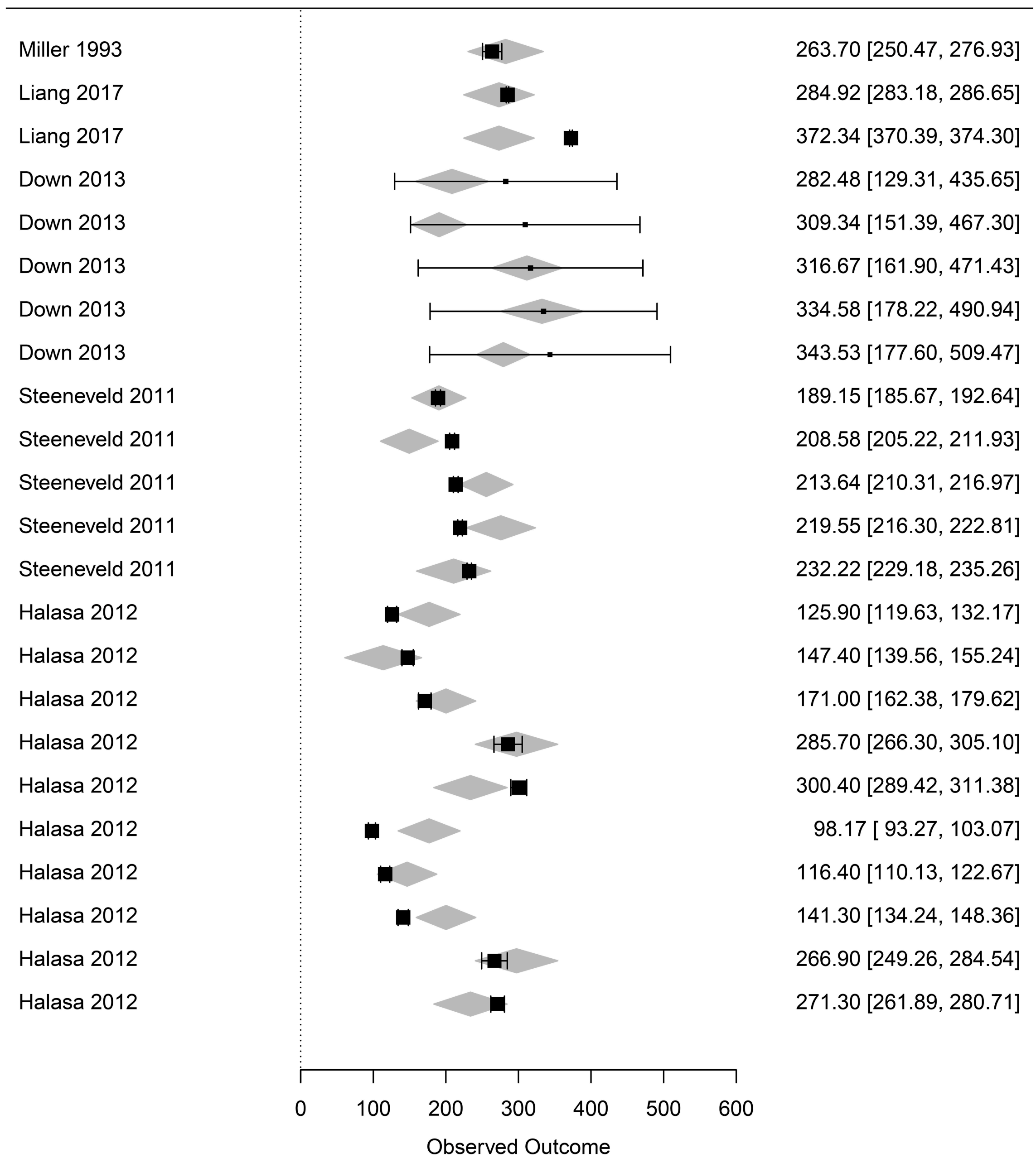

FIGURE 4 | Forest graph of the meta-regression including moderators in group C (see **Table 1**). The column on the right refers to the mean loss per case with the corresponding confidence interval (in brackets). The gray diamonds represent the effect size adjusted for the moderators included in the meta-regression.

reasoning focusing on the losses of mastitis is inappropriate and should be avoided. The present meta-analysis does not provide additional information since the economic reasoning in most of the raw models used in the present meta-analysis was biased. Recent literature on economics of udder health has increasingly focused on the strategic management of mastitis instead of its losses (19–21). This appears to be an appropriate trend since it accounts for herd dynamics, short- and long-term issues and farmers' behaviors, for instance, through farmers' satisfaction not only relying on income optimization (utility). This is also a reason why some recent publications cannot be included in the present meta-analysis that focus on clinical mastitis losses. The exclusion criteria have also led to focus on the period from 1990 to 2019. The milk production environment has changed a lot worldwide during this period. The period was included in the present analysis as moderator but it was not significantly associated with the clinical mastitis losses. Altogether, the PRISMA procedure, the outcome

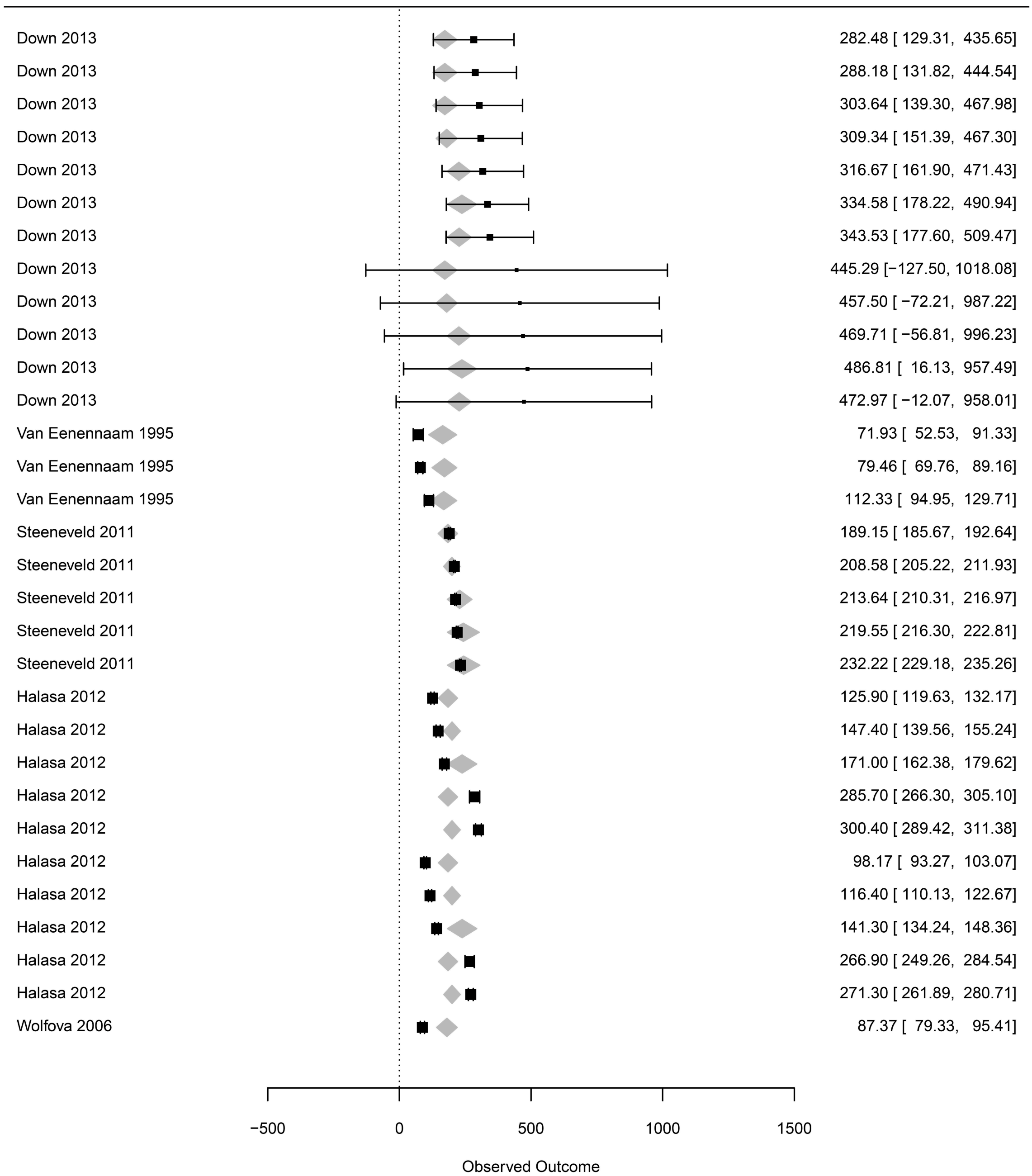

FIGURE 5 | Forest graph of the meta-regression including moderators in group D (see **Table 1**). The column on the right refers to the mean loss per case with the corresponding confidence interval (in brackets). The gray diamonds represent the effect size adjusted for the moderator included in the meta-regression.

studied, the period focused and the geographical restrictions have led to exclude many studies that deal with economics of mastitis.

The present work tried to explain the losses of clinical mastitis considering different groups of moderators (**Table 1**). The moderator groups B, C, and D (see **Table 1**) referred to the questions "is the moderator accounted for? (yes/no)," "can the size of the contributor (total monetary value) be linked to clinical mastitis losses?" i.e., "is the share of the contributor almost always the same?" and "can we summarize how the economic input parameters influence the total losses?," respectively. Moderator group B showed that factors were systematically included, scarcely included (adjustment for reduced feed intake), or almost never included (reproduction impact, pre-treatment diagnosis). These differences contributed to the large heterogeneity observed in the outcome of the present study. Unfortunately, moderators in group C were scarcely reported. Publications precisely reported the main contributors included in the economic assessment (moderators in group B), but most of them failed to clearly describe the value of this contributor (moderators in group C). This is a key limit to evaluating whether the share of the contributors substantially changed between publications, and it does not allow here to draw a conclusion on the external validity of the literature, even if it is extensive. Such a standardization would require precise lists of items to be reported and clear procedures to be followed to perform and evaluate the analysis, as it exists for other scientific approaches (see PRISMA as the reference method for meta-analyses). In a companion paper focusing on BVD, the same limits were highlighted, and the contributors of the total losses of BVDV infection could not be defined precisely due to imprecision in the included contributors and a lack of clear reporting of the values of each contributor (4). Last, the values of the economic parameters had almost no association with the clinical mastitis losses. This is also due to unclear results in the publications and the low variability within the values of the moderators. In addition, no association was reported between the input values and the outcome for moderators such as price of milk or labor (**Table 1**), although the number of trials included was moderate to high and the range of the values appeared to be appropriate for regression. The wide range in the values of milk price without any significant association was in opposition with the statement that the price of milk influences the losses of the disease and may be an item to consider to adapt the disease management strategy to the market context, which is often reported in sensitivity analyses in publications and in the field. The present results do not support such a relationship. Based on the present results and due to the heterogeneity, the conclusion is that the scientific community should be very careful to use the monetary values from one study out of its context or for their own study design, because the mastitis losses depend on many other factors which cause the heterogeneity that could not be explained by the factors considered in the present study.

CONCLUSIONS

The present work proposes an estimation of the losses of clinical mastitis for different etiologies. It failed to elucidate which contributor mainly influenced the losses of clinical mastitis and did not highlight any relationship between the price of milk or labor and losses due to clinical mastitis. This supports the avoidance any economic reasoning focused on the losses of each case of clinical mastitis since such a reasoning is inappropriate from an economic point of view. The internal and external validity of the losses evaluation is highly questionable in the case of clinical mastitis. These results also highlight the need for standardization on how economic assessments of losses due to animal diseases should be performed. This includes both methods and ways results are presented.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

DR and TG designed and performed the analysis. BP, AF, PS, and GL contributed to the analysis, reviewed, and revised the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2020.00149/full#supplementary-material

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Network Analysis of Cattle Movement in Mato Grosso Do Sul (Brazil) and Implications for Foot-and-Mouth Disease

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Foot-and mouth disease (FMD) is an animal disease that generates many economic impacts and sanctions on the international market. In 2018, Brazil, the world's largest beef exporter, had the recognition by World Organization for Animal Health (OIE) as a country free of FMD with vaccination and proposed to withdraw FMD vaccination throughout the country, based on a 10-year schedule, beginning in 2019. Therefore, Brazil needs studies to help the decision-making process, particularly regarding the availability of resources for strengthening of official animal health services. The state of Mato Grosso do Sul (MS) was chosen to be analyzed for three reasons: the size of its herd, the economic importance of its livestock and its location—which lies on the border with Paraguay and Bolivia. The current study adopted the Social Network Analysis and performed an exploratory analysis of cattle movement in MS. The most central municipalities in the networks were identified and they can be seen as crucial in strategies to monitor animal movement and to control outbreaks. The cattle movement networks demonstrated to be strongly connected, implying a high-speed potential FMD diffusion, in case of reintroduction. In a second stage, we performed an exploratory analysis of animal movement within the state, assuming distinct points in time for the identification of animal origin. The results of the analysis underlined the need and relevance of investing in animal control, sanitary education for producers and equipment and technologies to assist in the early detection, diagnosis, and eradication of outbreaks in a fast and efficient manner, preventing a possible outbreak from spreading to other regions.

Keywords: animal movement, social network analysis, foot-and-mouth disease, potential impacts, Brazil

INTRODUCTION

Foot-and-mouth disease (FMD) is considered the most important infectious animal disease in terms of economic impact in the world (1–3). In addition to causing losses in production, it generates strong reaction from animal health systems and restrictions on animal trade inside and outside the affected country. Understanding the impacts of FMD is essential in defining the level of resources expended for its control and eradication.

Although FMD causes low mortality in infected adult animals, it causes high mortality in young animals and fetuses (4). The frequency of outbreaks and the large numbers of animals and species affected in each outbreak result in high impacts for the affected country. Outbreaks of FMD cause production losses, such as reduced milk production and contraction in livestock growth rates (1).

FMD transmission occurs through direct or indirect contact with infected animals and animal products; by humans and non-susceptible animals, vehicles and equipment that had contact with contaminated animals; as well as by soil, air and water (1). It crosses international borders through trade of infected animals and animal products. Its economic effects are amplified by imposed restrictions on international trade by importing countries (5).

The World Organization for Animal Health (OIE) endorses national programs for FMD control and provides official recognition of disease status of Member Countries, as well as establishing procedures to be followed in case of outbreaks (6). OIE orientation in crises is strategic from the economic point of view, particularly for trade, since many countries follow its guidelines to access markets in sanitary risk situations. Each type of classification leads countries to a different way of addressing the impacts of FMD, including the focus regarding research, prevention, and control (7).

In March 2017, Brazil launched a proposal to suspend vaccination against FMD throughout the country and, in May 2018, it was recognized as FMD-free with vaccination by OIE. The proposed withdraw of FMD vaccination is based on a 10-year schedule and is described in the "National Foot and Mouth Disease Prevention and Eradication Program (PNEFA): strategic plan 2017–2026" (8).

The National Foot and Mouth Disease Prevention and Eradication Program (PNEFA) was the first and largest consolidated animal health program in Brazil. The main discussions on animal health in the country and the most important health policy focus on FMD. The proposal of PNEFA 2017–2026 will promote several changes in the program and this is a topic currently under discussion.

To implement PNEFA 2017–2026, Brazil needs studies to help the decision process regarding the availability of resources to strengthen the official veterinary service, as well as to elucidate possible impacts of this structural change for the beef sector and the agencies committed to the animal health policy. The current study intends to help with this purpose.

In order to highlight the importance of animal control to prevent health crises, in particular arising from the presence of FMD outbreaks in an exporting country of the magnitude of Brazil, this paper aims to show how the movement of animals could influence the spread of an FMD outbreak. The state of Mato Grosso do Sul (MS) was selected for this analysis due to its relevance in national livestock breeding.

MS State is a major Brazilian cattle producer and supplier of calves and beef cattle to other states, representing 10% of the national herd—21 million heads (9). MS has borders with Paraguay and Bolivia—two countries in which livestock farming constitutes a relevant economic activity –, as well as with other Brazilian states that are important for the national beef cattle and dairy cattle raising (Mato Grosso, Goiás, Minas Gerais, São Paulo and Paraná). The extension of the international border enhances the risk of virus entry, and the spread from MS to other states can happen quickly, due to the significant flow of animals from this state to the rest of the country.

Beef cattle is the most important activity in the state's agribusiness gross domestic product (GDP) and it is also important for other Brazilian states. The Animal Transit Guides (Guias de Trânsito Animal—GTAs) analysis indicates that, in 2015, MS sent about 484,527 animals to other states.

The purpose of this study was to identify the flows of bovine animals between municipalities in MS by use of network analysis and to identify the most central municipalities in the network to show the importance of promoting more reinforced surveillance actions in these locations.

Epidemiological logic requires considering other susceptible animals, but this study focuses the analysis on bovine animals. The swine livestock chain is considered highly integrated in Brazil, being more organized, and more rigid in terms of health than the cattle livestock chain. Pigs move significantly less than cattle, and live a relatively shorter time. In addition, the properties that deal with pigs follow strict sanitary and sterilization protocols in their facilities. Furthermore, pig raising in the state of MS is not as strong as cattle, therefore, the second was chosen for the present study. In addition, the Brazilian buffalo herd is not significant compared to the bovine and swine herds, so the movement of animals of this species was not considered in this research.

MATERIALS AND METHODS

This study was conducted using Socioeconomic Network Analysis (SNA). In veterinary epidemiology, SNA is a statistical tool to evaluate the movements of animals that have already occurred, extrapolating to what could happen in the future. This allows evaluating the impact of disease control measures according to the network structure and predicting the potential size of the epidemic after the introduction of a highly contagious disease (10). SNA structure allows the identification of surveillance, intervention and control targets (11–26).

A network is represented by a graph, which consists of a set of vertices and lines, called nodes and links, respectively (27, 28). In this study, the nodes refer to the municipalities of MS State and the links represent the movement of animals.

In order to analyze the centrality of the municipalities within the networks, we calculate their: (i) input and output degree; (ii) weighted input and output degree; and (iii) betweenness centrality. The degree centrality measures the number of neighbors of a node. Nodes with high degree are considered hubs. In a directed network, such as an animal movement network, the indegree shows how many neighbors send animals to the analyzed node and the outdegree shows how many neighbors receive animals from the analyzed node. The weighted degree considers how many animals are sent and received, that is, it considers the thickness of the link, not the number of neighbors. The betweenness centrality is based on the idea that a node is more central if it is more important in the transmission intermediation within the network (29).

These measures show the number of nodes with which the node in question negotiates, as a receiver and as a supplier, and the node's transmission intermediation within the network. Higher levels of connectivity are indicators of vulnerability of commercial networks to infectious diseases (30, 31). The most central nodes are those whose removal would more easily interrupt the transmission process in the network (10, 32).

SNA shows that: (i) in a dense network, the animal movement is easier and faster than in a sparse network; (ii) in a disconnected network, animal movement will be slower and less embracing than in a connected network; (iii) the greater the neighborhood of a node within the network, the greater its probability of receiving the animal; (iv) a central position increases the probability of receiving the animal; (v) movement started in a central node is faster than from a peripheral node (28).

Seeking to evaluate the potential risks of FMD in Brazil, networks were built based on the registers of bovine animals circulated in the state of Mato Grosso do Sul—obtained from the Animal Transit Guides (Guias de Trânsito Animal—GTAs), which are an official control data of animal movements within and between Brazilian states—for 2015. It is worth mentioning that epidemiological logic requires considering other susceptible animals, but this study focuses the analysis on bovine animals.

The GTAs show daily records of the movement of animals within the state and provide the municipalities of origin and destination, the number of animals moved and its purpose. In the original database, these purposes were: slaughter, fattening, reproduction, sports, auctions, exports, exhibitions and service (traction). For simplification, these purposes were aggregated into four groups: slaughtering, replacement (including fattening and reproduction), events (including sports, auctions and exhibitions), and others (including exports and service[1]).

The two purposes that stand out are replacement and slaughter. It is important to differentiate between them, because animals moved for replacement still live, while animals moved to slaughter do not. Thus, the purpose of the movement can influence the process of infection transmission within the network, because animals moved to slaughtering do not continue the transmission process.

The GTA data are not published and were obtained in 2017 by the Center for Advanced Studies on Applied Economics (Centro de Estudos Avançados em Economia Aplicada—Cepea), directly with the Ministry of Agriculture, Livestock and Food Supply (MAPA)[2], although the data are compiled by the official veterinary service of the state of MS. The database for 2015 comprised 416,743 GTA issued by the MS state. The official veterinary service has information on animal movement at farm level. However, for the accomplishment of the present study, only aggregated information at the municipal level was made available.

In addition to animal movement, data on the total number of animals of the Brazilian cattle herd were used. These data are available on the website of the Brazilian Institute of Geography and Statistics (IBGE), detailed by municipality and refer to the year 2015 to be compatible with the animal movement data (33). The Brazilian cattle herd is measured only at the end of each year and, therefore, this data is annual.

Animal movement data are recorded daily and they were analyzed on a daily basis in the construction of the networks. However, descriptive statistics on animal movements were done on monthly and quarterly basis in order to find more expressive and seasonal movement patterns throughout the year.

Daily animal movement networks were constructed. We used R software (34) to compile the animal flows with "dplyr" package (35). This package forms networks in a way that avoids networks with multiple links between two municipalities on the same day, so that the visualization of the networks was clearer—but the number of animals moved between municipalities was maintained.

For lack of more detailed data—such as the absence of data on the origin and destination of the movement in other states—the transit between states, inward and outward MS, was excluded from the analysis of the animal movement networks. The daily networks were built for the cattle movement within the state using GTA data. These networks are composed of all the municipalities of the state ($n = 79$) and the flows of animals between them.

From the networks obtained, we analyzed the dynamics of the registered flows and the descriptive statistics of socioeconomic networks for the state with "igraph" package of R software (36). Then, we evaluated the density of the daily networks and their centrality measures, showing the most central and, therefore, most vulnerable municipalities. We also generated the visualization of the daily networks for the whole year of 2015.

In the second step, also performed in R, we did an exploratory analysis of animal movement within the state, assuming distinct points in time for the identification of animal origin. This analysis aimed to show the risk of an animal contacting animals from other locations in the state, implying a potential spread of diseases—more specifically, FMD. In addition, we considered different time periods for the identification of the animal to show that time can directly affect the number of animals contacted, which consequently increases this potential transmission risk.

The exploratory analysis was based only on the animal movement data. No epidemiological simulation was performed. Thus, the results only evaluate the patterns presented by the movement of cattle. It was assumed that an animal was found in a certain municipality and that this animal left its hometown a few days before. Two scenarios were constructed: a scenario in which the animal left its hometown 3 days before discovery and a scenario in which the animal left its hometown 7 days before discovery.

[1]There is no significant movement of animals for service and, when such movement exists, animals generally do not travel long distances nor are they sent to several other properties. Therefore, this purpose was grouped together with exports.

[2]GTA data is confidential and belongs to the Brazilian Ministry of Agriculture Livestock and Food Supply. Access to the most recent data for updating the study before publication was not authorized.

After the definition of the day on which the animal was identified, the animal flows of the municipality where that animal was found were analyzed for the previous days. We did this analysis in order to calculate how many municipalities the animal could have passed during 3 days or 7 days, depending on the scenario. From the number of municipalities in which it could have passed, we calculated how many animals it could have contacted during the transit until it reached its final destination. To this end, a strong assumption was made: the animal that left its hometown could contact all animals in all the municipalities where it passed through. The number of bovine animals in each MS municipality was kept constant over the year, because Brazilian herd data are annual. For each scenario, 10,000 repetitions were performed to obtain frequency histograms. To construct these histograms, we considered all municipalities as a possible starting point and each one of the 365 days a year.

Figure 1 shows the representation of a theoretical analysis for a 3 day scenario. An animal leaves its municipality of origin on day 1 (animal circulated by the discontinuous line). Its origin could be any municipality in the state. Over the days, animals pass through some municipalities, until day 3 when an animal with clinical signs of disease is identified in municipality J. During this period, the animal could have followed different trajectories within the network. The different possible paths affect the number of municipalities it could have passed through and the number of animals, which it could have had contact to. In other words, movements of bovines happened from the municipality of origin to B, to F and to J on specific dates, and therefore the marked animal might have been moved along these links.

The histograms constructed in this stage were based on 10,000 processes as the one described above, considering the possibility of any municipality in MS as the origin and taking into account the GTAs registered in 2015. These histograms show the proportion of animals in the state that could be contacted by the animal in transit, distributed according to each iteration of the 10,000 performed.

In the third stage, we explored different cattle movement patterns from central and peripheral municipalities in the animal movement networks of MS. One municipality was selected as representative for central municipalities (Corumbá), and one for peripheral municipalities (Sete Quedas). We considered the different number of animals contacted according to the municipality of origin of the animal found. Then, it was possible to analyze how many days the animal would take on average to

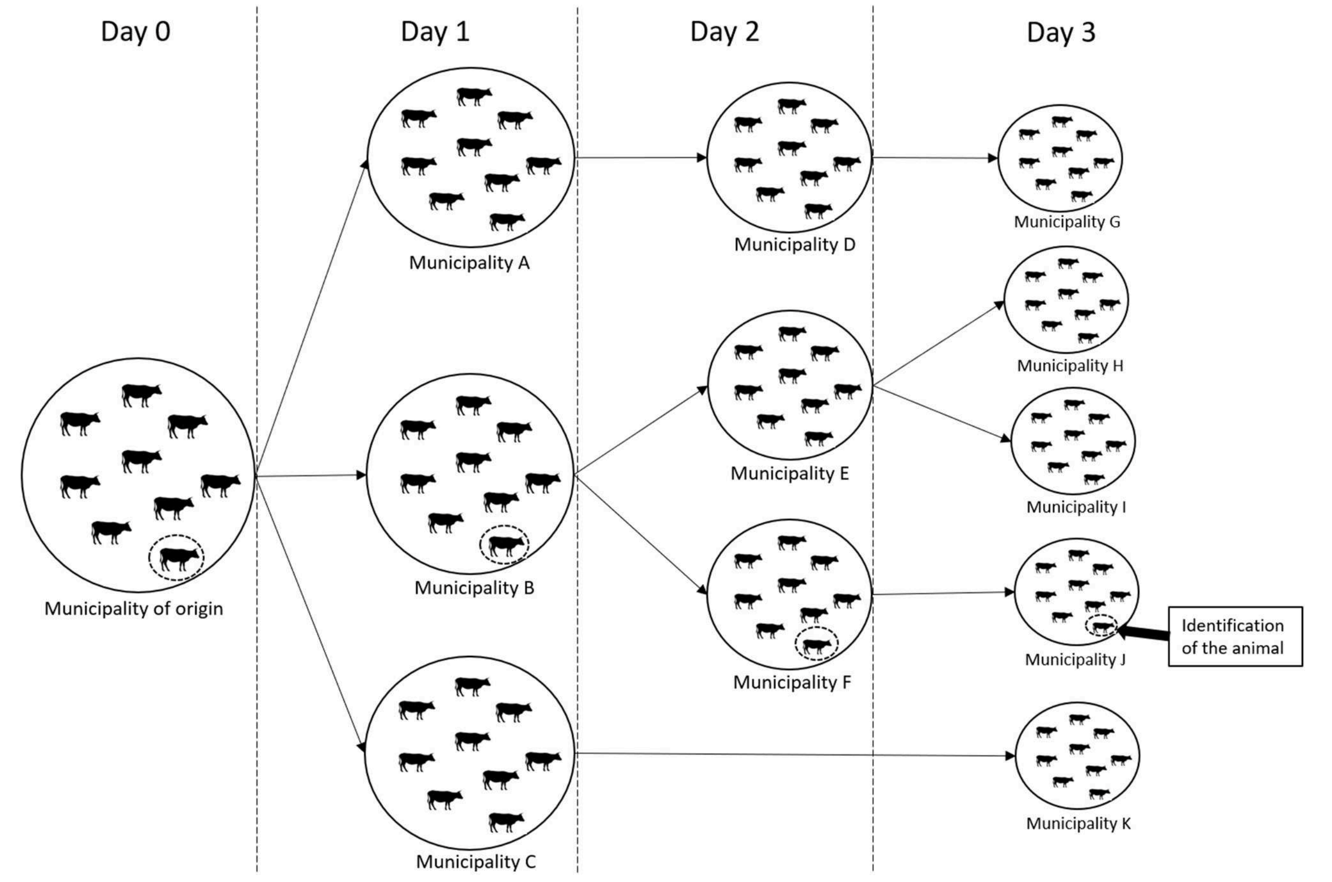

FIGURE 1 | Representation of a theoretical network analysis for a 3-day scenario. Source: Authors' elaboration.

reach all municipalities in the state, depending on its municipality of origin.

Diffusion curves were constructed for the movement of the animal. The movement pattern is characteristic of a chain reaction in which a municipality sends the animal to one of its direct neighbors, which, in turn, send it to one of their direct neighbors in the next stage, and so on, forming a curve. These curves were constructed to emphasize that the animal movements originated in central municipalities in the network occur more quickly, offering a greater risk of spreading animal diseases to other municipalities—in comparison to the movements that begin in peripheral municipalities. We seek to demonstrate the importance of strengthening control and monitoring actions in central municipalities in order to identify risks more efficiently and quickly.

RESULTS

The map in **Figure 2** shows the location of MS municipalities and the size of their cattle herd, providing an overview of the geographical location and cattle distribution in the state. From the map, we observe that Corumbá is the largest municipality in the state, both territorially and in herd size and it is bordered by Bolivia; while Porto Murtinho, Bela Vista, Ponta Porã and other municipalities are located on the border with Paraguay. The

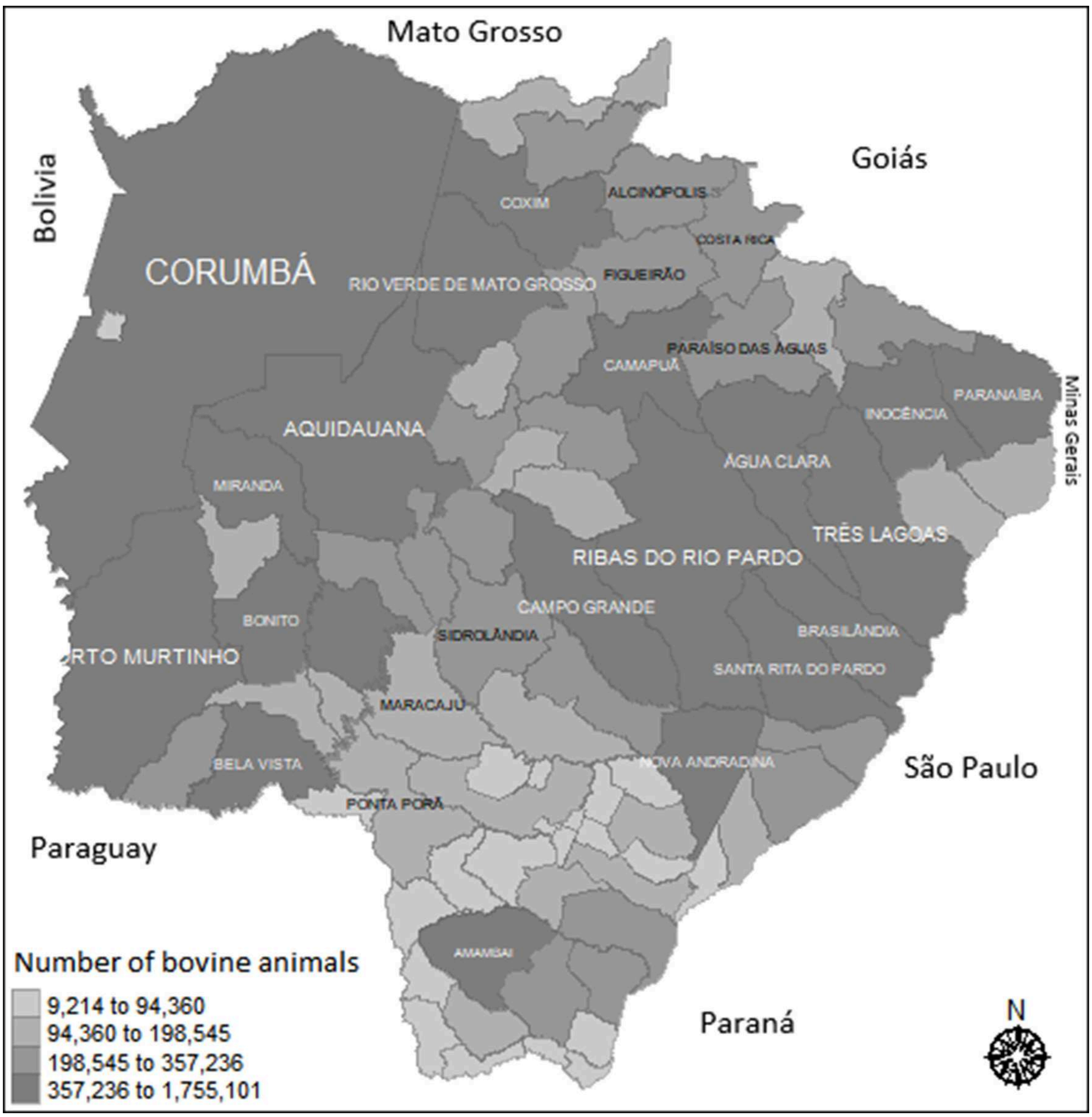

FIGURE 2 | Distribution of bovine animals in Mato Grosso do Sul: 2015. Source: Elaborated from IGBE data (2016). The gray scale represents the number of animals in the municipality. Darker colors show where there are more animals.

international border area and the area near the border with the states of São Paulo and Minas Gerais (Paranaíba, Água Clara, Três Lagoas, Ribas do Rio Pardo) represent the majority of the cattle herd of MS state.

Characterization of Animal Movements

In 2015, 12.35 million bovine animals were moved within MS, of which 65% were for replacement, while 30.3% were for slaughter and 4.7% for events; only 95 animals were moved for other purposes. The number of animals moved between the municipalities of MS varied across the months, not only in the number of registered GTAs (number of transactions) but also in terms of animals moved monthly, with the most movements in June and July and the fewest in November (**Figure 3**). In general, the predominant purposes in animal movements were slaughter and replacement, distributed throughout the quarters (**Table 1**).

The 10 municipalities with the largest herds of the state are: Aquidauana, Camapuã, Campo Grande, Corumbá, Coxim, Porto Murtinho, Ribas do Rio Pardo, Rio Verde de Mato Grosso, Santa Rita do Pardo, and Três Lagoas. These municipalities were among the top 10 recipients and senders of animals within the state.

In the same year, MS remained a net exporter of cattle, sending additional 484,527 animals to 21 other states and receiving 280,421 animals from other Brazilian states. Nearly 58% of the total sent was intended for slaughter, while only two animals were received for this purpose. Among animals transported to other states, 42% were destined for replacement; while that purpose accounted for about 92% of the total received. The main recipient of animals for slaughter and replacement was the state of São Paulo, while Minas Gerais was the main supplier of animals for replacement to MS.

During 2015, the 10 municipalities that received the most animals for slaughter purposes concentrated a significant portion of the total transported volume—73.9%. These municipalities accounted for <14% of the state cattle herd. Considering the animals sent for slaughter, the flows were less concentrated, with the top 10 municipalities accounting for <33% of the total animals moved with this purpose and more than 32% of the total state cattle herd.

The 10 municipalities that received the most animals for replacement purposes concentrated 31% of the total flows. These municipalities accounted for almost 35% of the state cattle herd. Considering the animals sent for replacement, the top 10 municipalities accounted for 40% of the total animals moved with this purpose, concentrating about 35% of the state herd.

Daily Networks of Animal Movement in Mato Grosso Do Sul

A network was built for each day of 2015 and the three proposed indicators of centrality were calculated for all municipalities of the state. For the degree centrality, Campo Grande, Naviraí, Nova Andradina and Terenos showed the highest input degree, which means that there was a greater local density in their neighborhood, since there was a greater number of direct neighbors (or municipalities), acting as the main receivers of animals (**Figure 4**). Among them, Campo Grande stood out for

TABLE 1 | Total cattle sent for slaughter and replacement in MS: 2015.

Period	Slaughter (in millions)	Replacement (in millions)
1st quarter (January–March)	1,04	1,75
2nd quarter (April–June)	0,93	2,16
3rd quarter (July–September)	0,88	2,23
4th quarter (October–December)	0,89	1,88

Source: Elaborated from GTAs.

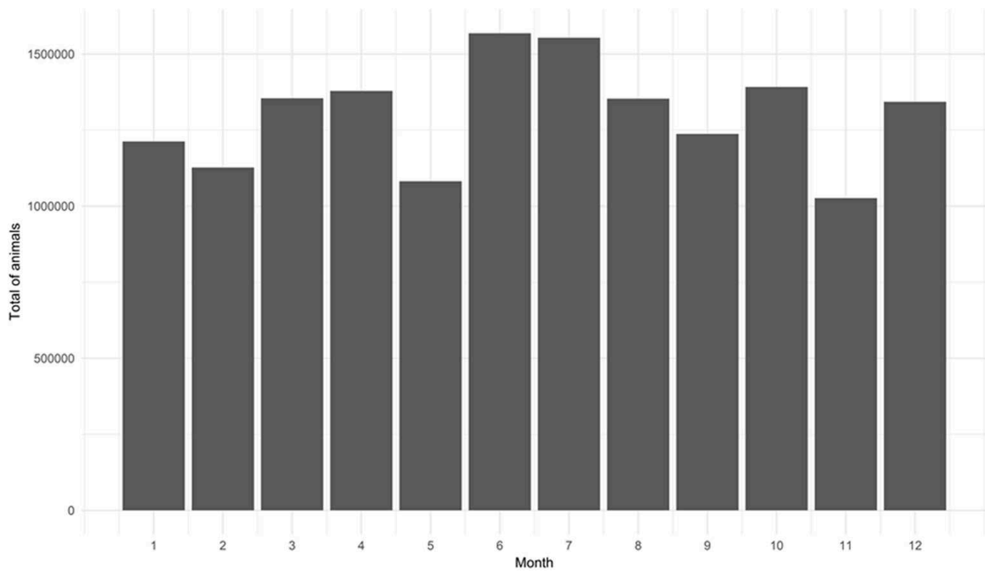

FIGURE 3 | Monthly total of animals moved in 2015 according to Animal Transit Guides (GTAs) issued in Mato Grosso do Sul. Source: Elaborated from GTAs.

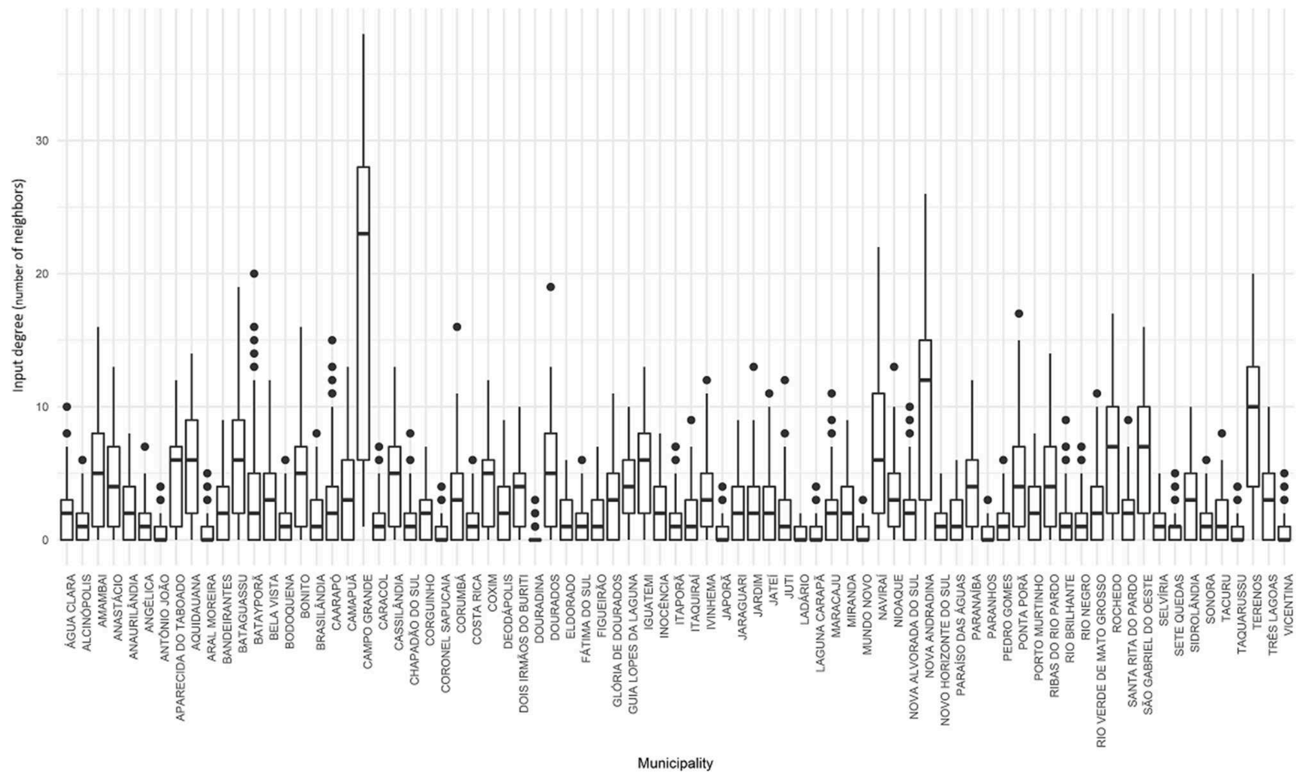

FIGURE 4 | Input degree for cattle movement in Mato Grosso do Sul: 2015. Source: Elaborated from GTAs. Number of daily partners of each municipality distributed in quartiles (boxplots).

having a median of direct neighbors superior to that of the other municipalities (above 20).

We can also notice that, for Campo Grande, the variability was also high when compared to the observed in the other municipalities. Thus, median and values observed in the last quartile were significantly higher than those for other municipalities. This can indicate that Campo Grande is, on average, more vulnerable to an FMD outbreak, since it receives animals from many different municipalities, presenting a higher probability of receiving infected animals in the event of an outbreak.

On the other hand, the output degree average values were not so heterogeneous (**Figure 5**). These values showed a dispersion among the municipalities, but they were not as discrepant when compared to the input degree. In this case, Aquidauana, Campo Grande, Corumbá and Ribas do Rio Pardo stood out, presenting medium values >15 direct neighbors—although Campo Grande was still most extreme. In other words, these municipalities acted as the main animal suppliers within the network, as they sent to a greater variety of municipalities. In epidemiological terms, they could function as major spreaders of the FMD virus, in case of infection—spreading it to an expressive portion of the state.

In the case of the weighted input degree (**Figure 6**), the municipalities that stood out for receiving more animals, in median values, were Campo Grande, Dourados, Glória de Dourados and São Gabriel do Oeste. The quantity of atypical values[3] was also highlighted in this figure, where each of the points outside the boxplot represents a specific day in which there was an extreme movement (in number of animals) when compared to the values predominant in the sample. These municipalities, therefore, would be more vulnerable to an outbreak of FMD because they receive more animals than the rest of the state.

Corumbá, Glória de Dourados, Ivinhema, Jateí and Ribas do Rio Pardo stood out in terms of weighted output degree (**Figure 7**). Again, there was a significant number of outliers in the distributions for each municipality. These central nodes, according to this measure of centrality, also constitute potential large spreaders of many infectious animal diseases, including FMD virus, by sending large numbers of animals to other municipalities within the state.

The betweenness centrality showed which nodes would cause the reduction of the network connectivity if they were removed, thus slowing down the transmission process. Campo Grande, Nova Andradina, Ribas do Rio Pardo and Terenos were the nodes that played a major role in the intermediation of flows between the different municipalities of the network (**Figure 8**). Finding these nodes with high intermediation helps to understand who can control the animal flows from one part of the network to

[3]The atypical values (outliers) here are the observed values that were outside the upper quartile.

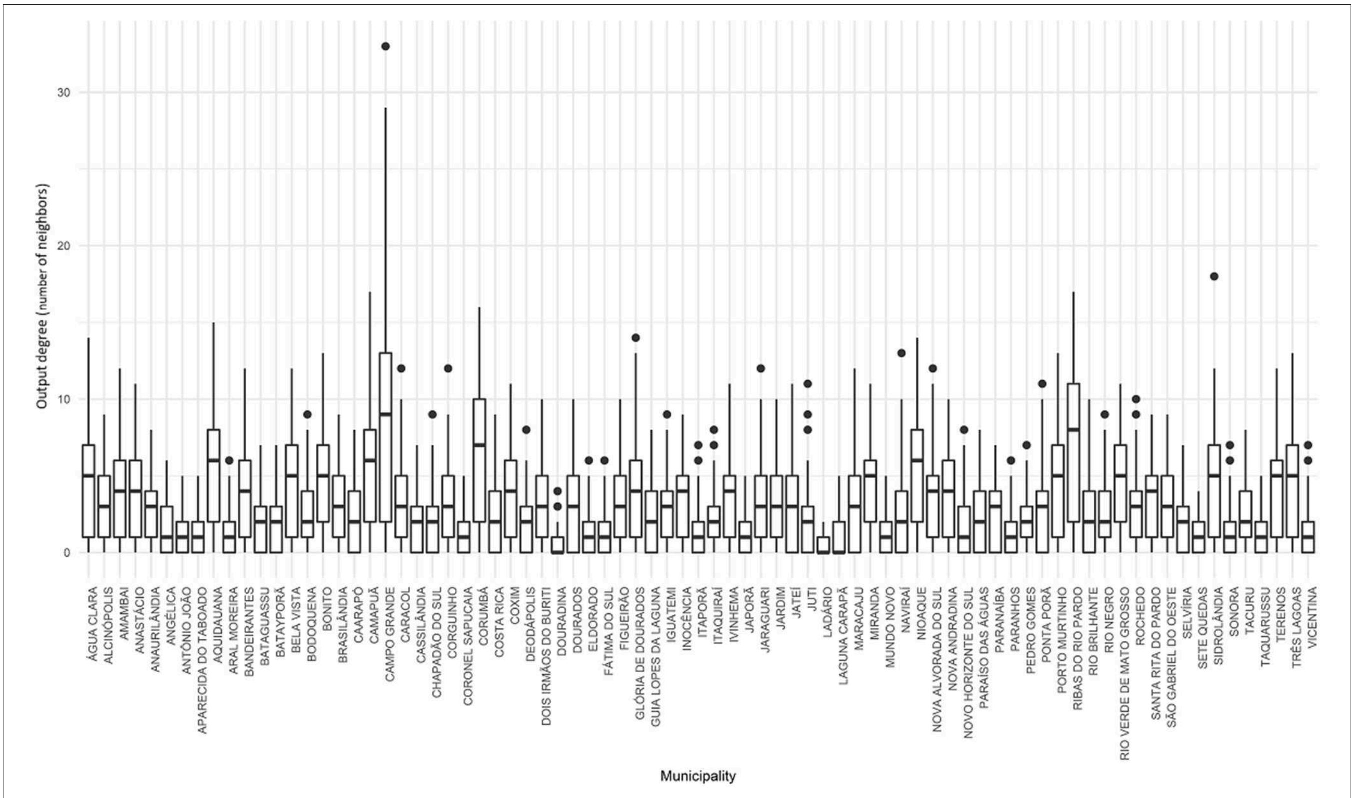

FIGURE 5 | Output degree for cattle movement in Mato Grosso do Sul: 2015. Source: Elaborated from GTAs. Number of daily partners of each municipality distributed in quartiles (boxplots).

another. The removal of these nodes fragments in the network could make it easier to control a sanitary crisis in a possible scenario of FMD reintroduction.

Figure 9 shows a representative view of the daily networks analyzed for 2015, for 4 days of the year (randomly selected by R), showing the most intense flows in the red color and the size of the herd in the gray scale. In some days of the year, the flow of animals between the municipalities is intense, while in other days this flow is reduced, with movement of few animals between neighboring municipalities. When examining the networks for every single day of 2015, in general and regardless of the month analyzed, there was a process of "supply" in the municipalities, which preceded more intense movements between central municipalities.

Exploratory Analysis of Animal Movement in Mato Grosso Do Sul

The first scenario assumed that a bovine animal was identified in a certain municipality 3 days after leaving its hometown. **Figure 10** shows the frequency histogram of the proportion of animals from the MS herd that could have contact with that animal.

January (1) and June (6), for example, had different potential impacts. In January, the repetitions were distributed almost uniformly over the proportion of the herd possibly contacted, with the vertical axis representing the number of repetitions that resulted in a certain affected proportion of the herd (x-axis). On the other hand, in June, many repetitions indicated a significant share of the herd that could be contacted by the animal, and many of them resulted in an impact on 100% of the MS herd.

In general, there was a great dispersion in the distribution of this impact, with a possibility of contact varying from 0 to 100%, depending on the animal's origin. This is because movements started in central nodes can be faster than those from peripheral nodes (with few direct neighbors and less significant animal flows).

The same exercise was repeated considering the distribution of the total number of municipalities that the animal could reach. The number of potentially contacted municipalities for a 3 day lag varied between 1 and 79 (total municipalities in the state), depending on the origin of the animal.

The second scenario considered that it took 7 days to identify the animal. The results were even closer to the upper limit (more extreme). Although there was dispersion in the distribution of impact on the herd (it could reach one animal or the entire herd), the probability of contact between the animal and the rest of the herd changed to a higher interval, between 75 and 100%, according to the distribution estimated (**Figure 11**). The number of reached municipalities also varied less between 1 and 79, concentrating between 60 and 79 municipalities. In other words, the probability of reaching most of the states' municipalities (or even all of them) was higher.

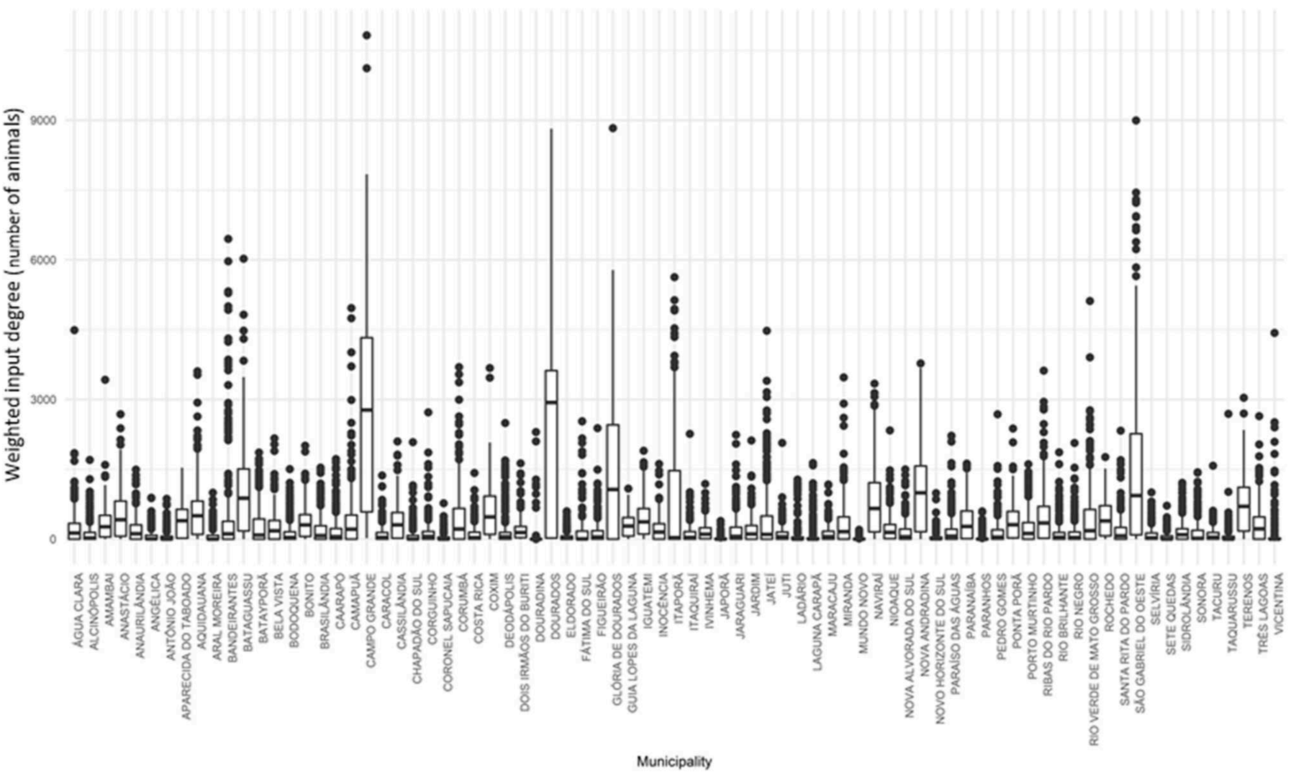

FIGURE 6 | Weighted input degree for cattle movement in Mato Grosso do Sul: 2015. Source: Elaborated from GTAs. Number of animals sent daily to each municipality distributed in quartiles (boxplots).

Differences Given by the Starting Point (Central and Peripheral Municipalities)

After studying the centrality measures of all the built networks, two municipalities (out of 79) were selected as starting point for animal movements, Corumbá as an example of a municipality with high centrality in the network, and Sete Quedas as an example of a peripheral municipality. In addition to appearing as one of the most central cities, Corumbá has the second largest cattle herd in the country, it is located on the border between Brazil and Bolivia, and, hence, is a high-risk municipality in terms of animals' entry (legal and illegal) by the border. Sete Quedas did not play a central role in the state's cattle movement networks, presenting considerably smaller animal flows than Corumbá.

This comparison demonstrated how different the movement speed was when the process originated from a central node and when, alternatively, it did from a peripheral node. In **Figure 12** it is possible to compare transmission processes with different starting points: Corumbá and Sete Quedas. The x-axis shows the number of days during which the animal could move and the y-axis shows the proportion of municipalities in the state that the animal could pass during the days of movement. The figure shows average cumulative diffusion curves for 2015, determined by the daily distributions of movements initiated in the two chosen municipalities. The points outside the curve are outliers observed throughout the year.

Both movement paths occurred in an accelerated way. However, the process started in Corumbá occurred faster than in Sete Quedas, as the former showed a steeper average curve compared to the second, underlining the high speed of animal movements started in a central node. If the animal originally left Corumbá, it would take 10 days to reach 100% of the state's municipalities on average. Whereas, if it departed from Sete Quedas, that period would increase to 14 days on average.

However, there was a notable dispersion, mainly, in the initial stage of the movement path—evidenced by outliers. Therefore, when considering the daily dispersion curves—instead of just the average curve—it could be possible to find S-shape curves; underscoring differences in movement velocity according to the observed day. It is important to note that these curves represent only the number of municipalities that the animal could pass through, not taking into account the number of animals that could have contact with it.

The fact that the mean curves did not have a S-shape can be a sign that the movement path in the network was very fast, even for the peripheral municipality (in the network) of Sete Quedas. This shows that, on average, the structure of the MS animal movement networks was very connected, which could accelerate

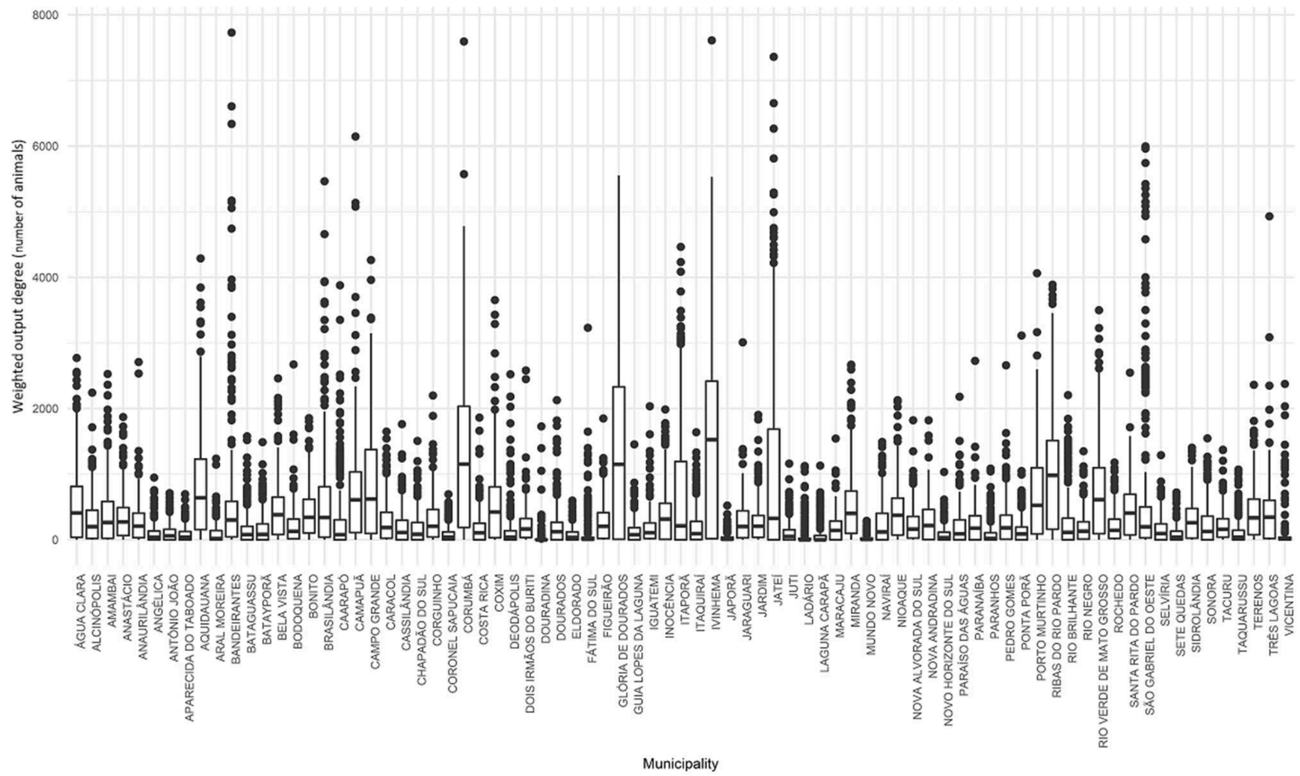

FIGURE 7 | Weighted output degree for cattle movement in Mato Grosso do Sul: 2015. Source: Elaborated from GTAs. Number of animals sent daily by each municipality distributed in quartiles (boxplots).

the speed of FMD propagation within the state, amplifying the outbreaks' impacts.

DISCUSSION

Geographical distribution of susceptible animals is among the factors influencing the spread of FMD virus. Consequently, it is important to identify the municipalities or areas where there is a high concentration of animals. In case of an infection with FMD virus, the greater the number of susceptible animals, the greater the risk of transmission between them. Municipalities or areas with high dense farms or animals are at the high risk for disease incursion, therefore, these areas should have intensive surveillance system in place.

The large number of FMD susceptible animals in the international border raises the probability of infection by any infected animals crossing from one country to another. The international border region of MS stands out as the most vulnerable to failures of inspection or possible illegal movements and should receive increased attention during surveillance actions—because there is a possibility of entry of susceptible animals from other countries in more than 600 kilometers of dry frontier.

In addition to the fact that surveillance at the international border is not 100% effective, the most recent FMD outbreaks in the region occurred in areas that were recognized as being free of FMD with vaccination (MS in 2005/2006 and Paraguay in 2011) and these outbreaks origin is still unknown (37, 38).

Amaral et al. (2) and Santos et al. (39) show that the international border of MS with Paraguay and the international border of Rio Grande do Sul (another Brazilian state) with Argentina and Uruguay are factors that represent a high risk of reintroduction of the disease by illegal or informal animal movements between countries. Therefore, it is important to consider the international border as a risk factor.

Animal movement is an important factor for the spread of FMD. MS can be in a situation of greater vulnerability regarding the introduction and spread of FMD virus by receiving many animals for replacement, predominantly. This is because animals for replacement coming from other states could be infected, in case of virus reintroduction in Brazil, and would remain alive when they entered the properties of MS—presenting a risk of virus transmission within the state herd.

For lack of more detailed data and for simplification purposes, the transit between states, inward and outward the MS, was excluded from the analysis of the animal movement networks. However, regarding epidemiological risk issues, it is important to emphasize the state's importance as an animal supplier to the rest of the country as well as a recipient of animals from other states—especially for epidemiological risk issues.

In case of reintroduction in MS, more intense movements of bovine animals, like in June and July, may result in a greater

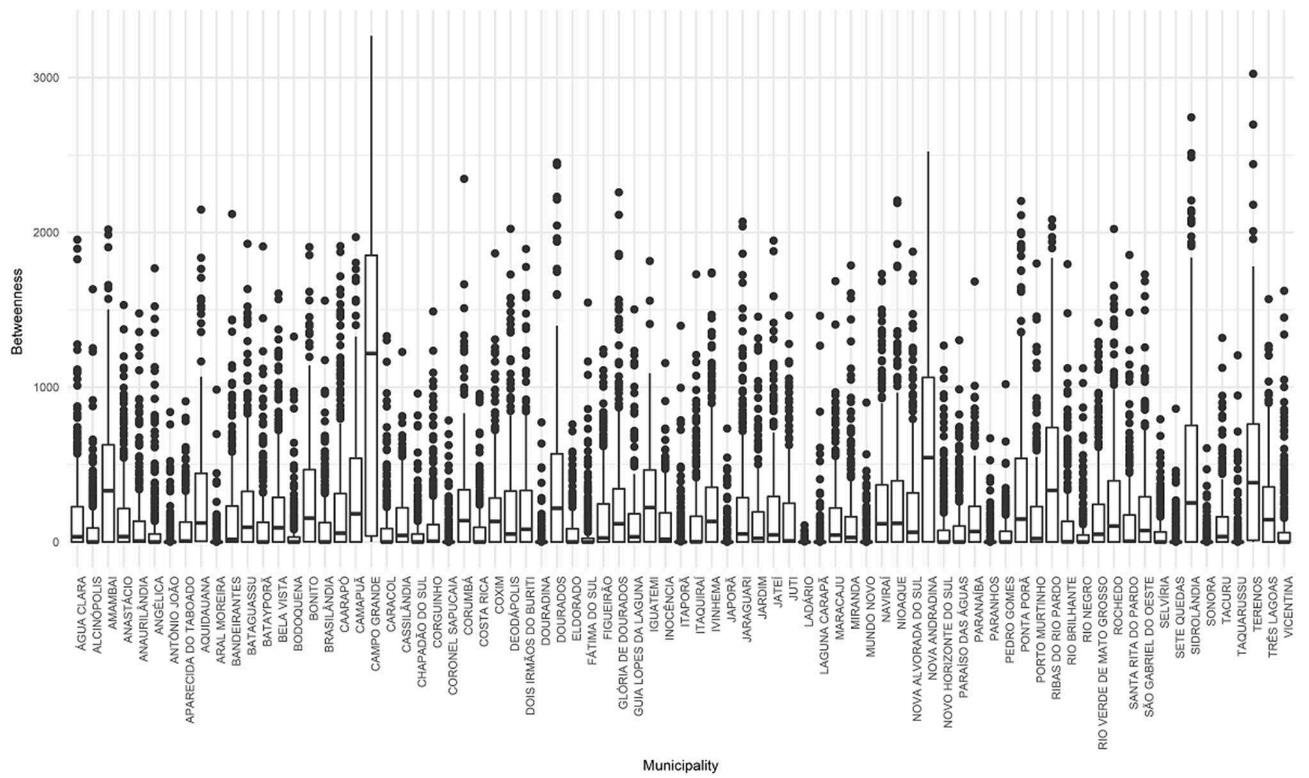

FIGURE 8 | Betweenness centrality for cattle movement in Mato Grosso do Sul: 2015. Source: Elaborated from GTAs. Number of relations intermediated daily by each municipality distributed in quartiles (boxplots).

risk of spreading the FMD virus. Therefore, it can be inferred that surveillance should be reinforced in this period, from the perspective of preventive planning for animal health policy. On the other hand, May and November showed a significant fall in the animal movements. The most likely cause is vaccination campaigns against FMD. During this period, producers gather their animals to apply the vaccine and there is less movement between properties. Therefore, the risk of transmission within the network in these months could be slightly lower than in the rest of the year.

The quarterly analysis of animal flows may reveal relevant elements related to the systems of production and their cycle, in terms of birth, weaning, fattening, and slaughter. Seasonality, inferred by the observation of the quarterly data, relates to the dry season, the confinement period and the usual time of commercialization of these confined animals, of calf birth and weaning age. Seasonal trends and temporal variation of animal movement are not uncommon in livestock networks already built for several other countries (18, 20–22, 24, 31).

In the first quarter, the slaughter rate was higher than in the other quarters; this is due to the precedence regarding the drought period. In the following quarter, when the drought season begins, the number of animals moved for slaughtering and replacement increased. In addition, in May, the weaning process of calves begins, which also justifies the increase of animals moved for replacement in the second and third quarters.

Cattle breeding has a certain seasonality throughout the year, divided in two periods: favorable and unfavorable. In the case of a tropical climate, as observed in the Center-West of Brazil, spring and summer (from September to February) are favorable for livestock, since they characterize the rainy season, improving the growth of the pastures. On the other hand, autumn and winter (from March to August) are unfavorable to the activity because the lack of rain causes the pasture to dry, thus reducing the food supply for the herd. This implies a higher slaughter rate, usually before the drought period, and, consequently increased animal movement during those seasons, justifying the greater movement observed during June and July.

If the FMD virus found its way to a highly-connected node on the network, many municipalities could become infected before authorities were aware of the virus circulation. This could hamper the control of the infection spread by the authorities, and lead to an outbreak explosion, depending on the level of the herd immunization. Immunized animals would spread the virus slower than in an unvaccinated population.

Regarding animal movement networks, we observed that measures of animal entry had greater heterogeneity than measures of animal exit, which has already been observed in animal movement networks in Argentina (20), France (40), and United Kingdom (19).

In general, the connectivity distributions of the network nodes were distorted. Most nodes had only a few connections and a

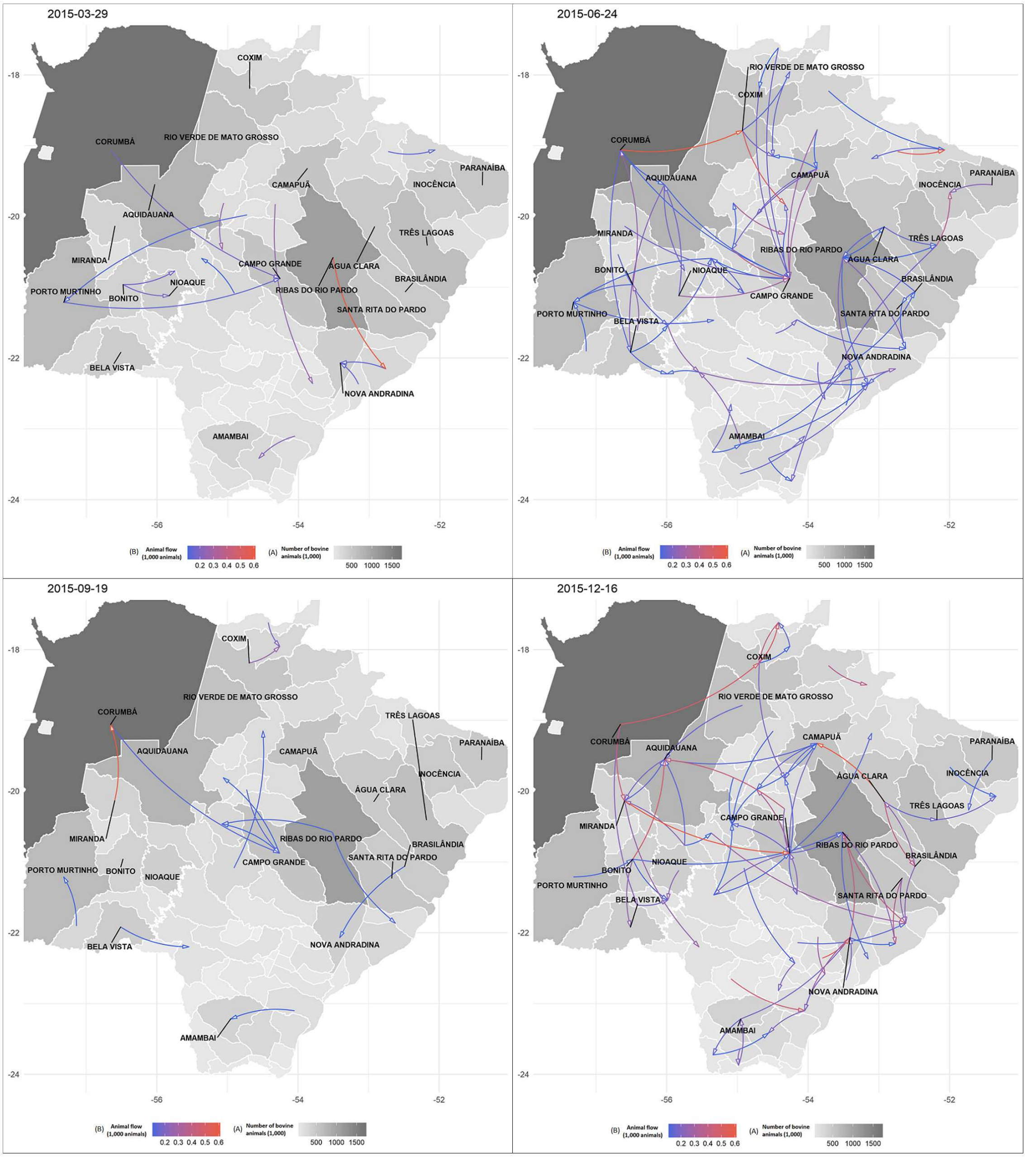

FIGURE 9 | Representation of four daily cattle movement networks in Mato Grosso do Sul: 2015. Source: Elaborated from GTAs and (33). **(A)** The gray scale represents the number of animals in the municipality. Darker colors show where there are more animals. **(B)** The red scale shows the number of animals moved between municipalities on that date. Blue denotes small number of animals. Purple represents a relatively average number of animals. Red indicates a large number of animals.

small minority of them had many connections. In some cases, the mean levels of connectivity were higher than the interquartile range of the data, highlighting the presence of outliers. In addition, the municipalities with the largest number of direct neighbors (considering input and output) were those that moved the largest number of animals, generally acting as major suppliers or receivers of animals. Campo Grande, for example, has a large movement of animals, consisting of a central node in the state's cattle movement networks. This central role may be due to the large slaughtering facilities located in this municipality.

Centrality measures pointed to the same municipalities, so they function as hubs of movement, with many connections within the networks. This means that the most central nodes in the networks are vulnerable in different ways and have a greater potential to infect a large part of the network in a possible outbreak. Therefore, during an outbreak, targeted surveillance

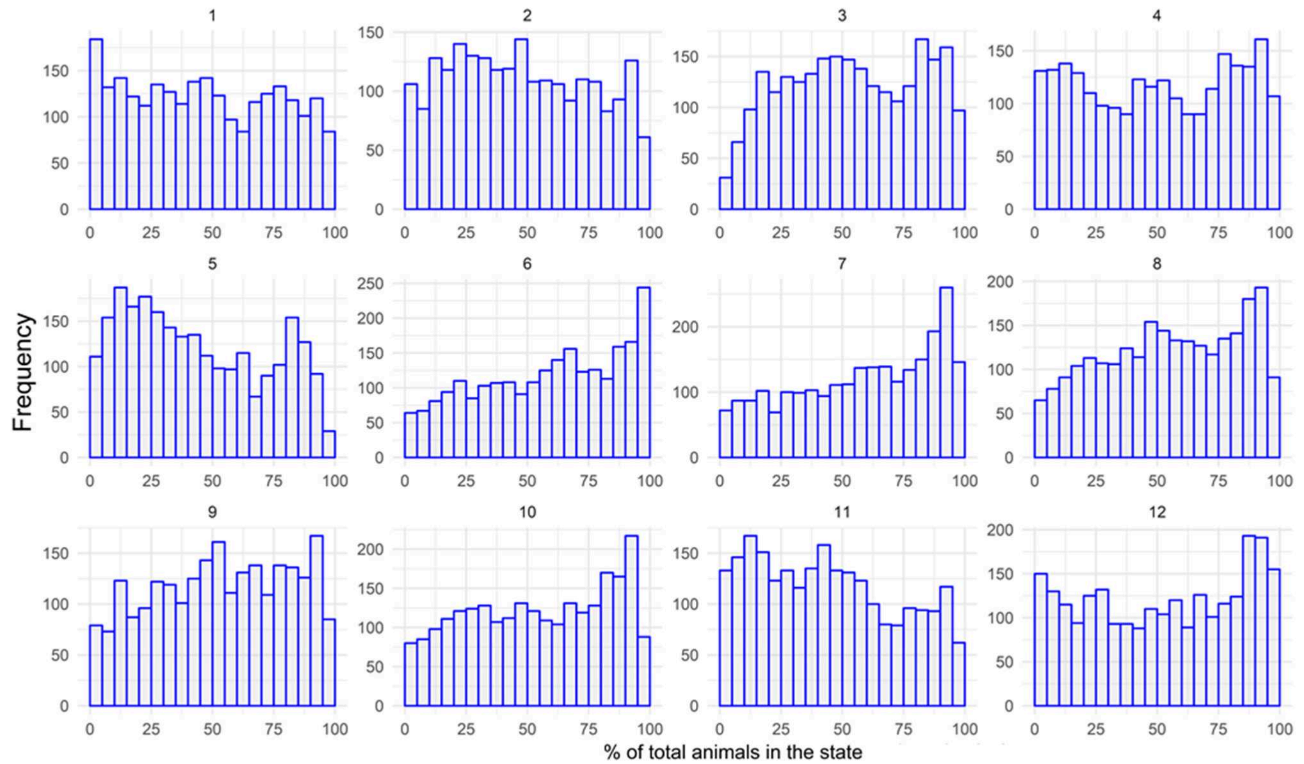

FIGURE 10 | Frequency histograms showing the numbers of iterations out of 10,000 (y-axis) which end with a certain percentage of animals contacted (x-axis) per month in Mato Grosso do Sul: 3 days of lag. Source: Elaborated from GTAs.

for central municipalities located in unaffected regions may have a greater probability of detecting the virus introduction into new areas. Likewise, movement restrictions directed at such municipalities may be more likely to prevent a wider spatial spread of the disease (24).

It is noteworthy, however, that this analysis considers only the movement of animals within MS State. If interstate animal movement were considered, the classification of central and peripheral municipalities could change, highlighting the importance of municipalities that in this study were classified as peripheral.

Animal movements were predominantly local (between geographically neighboring municipalities), although large municipalities were more likely to be involved in long distance movements (crossing the state). There was movement of animals throughout the whole state. However, movements of large quantities of animals were mostly local, between geographically close municipalities. This is important to notice because the frequency of animals moving over long distances is a factor that increases the risk of FMD infection and spread in the eventual reintroduction of the virus in the state.

The exploratory analysis based on the identification of an animal in a given municipality aimed to show the potential number of contacts with other animals along the trajectory of the identified animal. In this sense, the difference between the scenarios results shows that identification in a shorter period of time can significantly reduce the likelihood of contact between animals. In the context of an FMD outbreak, this analysis could indicate that the faster identification of animals that have moved from their origin reduces the probability of spreading the virus.

The analysis also shows that the transmission process is faster from a central municipality in the animal movement network, in comparison to a process initiated in a peripheral. This reinforces the importance of promoting more reinforced surveillance and control measures in central municipalities, as they could function as large hubs for the spread of the FMD virus in case of reintroduction in the state. The results show signs that FMD outbreaks originating in central municipalities could cause more damage than outbreaks started in peripheral municipalities within the state. This analysis could be expanded if the movement of animals between MS and other Brazilian states was considered. It would be possible to analyze the potential for spreading the virus at the national level.

In order to carry out the exploratory analysis, a very strong assumption was made: the animal in transit could have contact with all animals wherever it passed. This ended up overestimating the percentage of the state herd that could have contact with this animal. In a study with more detailed data, it would be possible to better consider this contact rate, in order to bring the results closer to reality.

The Brazilian official veterinary service has information on animal movement at farm level. However, for the

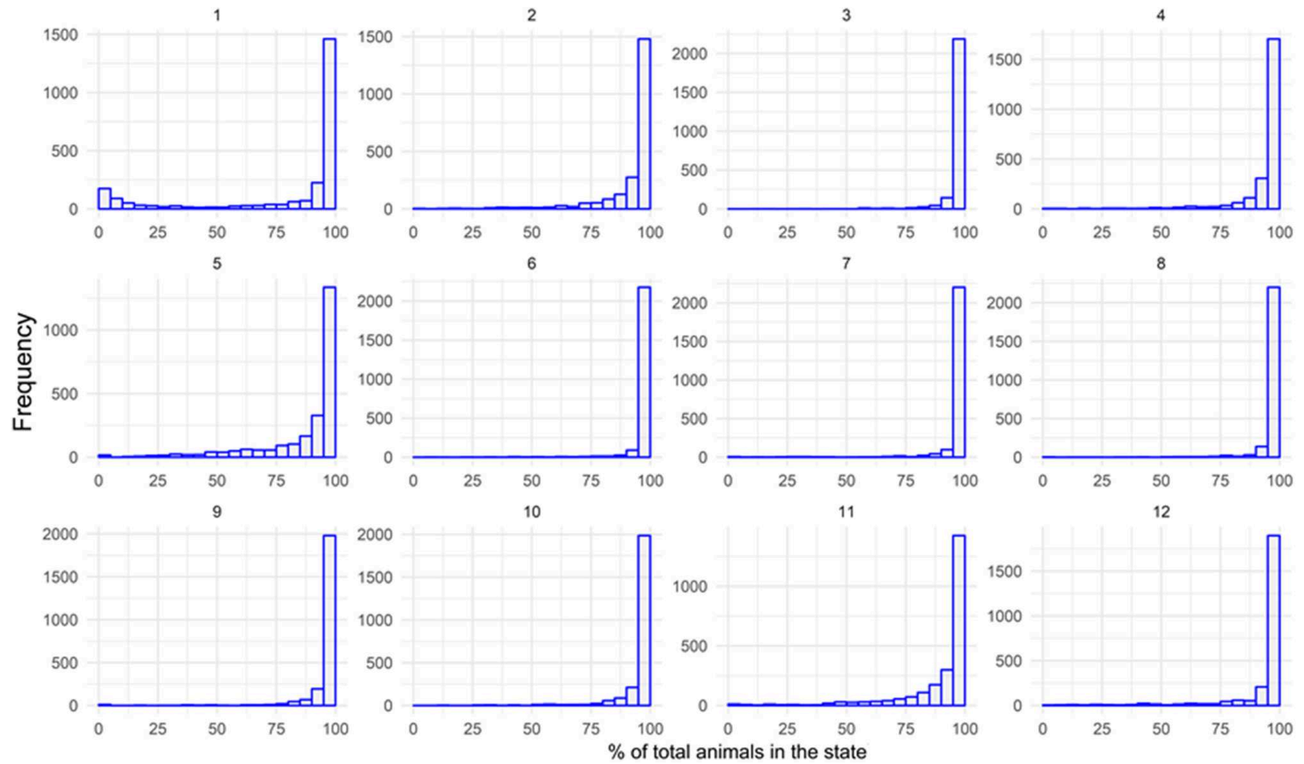

FIGURE 11 | Frequency histograms showing the numbers of iterations out of 10,000 (y-axis) which end with a certain percentage of animals contacted (x-axis) per month in Mato Grosso do Sul: 7 days of lag. Source: Elaborated from GTAs.

accomplishment of the present study, only aggregated information at the municipal level for 2015 was made available. The request to access the most recent data to update the study was denied, as well as access to detailed data.

This was a limitation that directly affected the results of the study. The analysis of centrality measures at the property level could reveal properties with a central role in animal movement networks, even though they are located in peripheral municipalities. This could assist in defining more efficient and effective surveillance and control measures than measures based solely on data analysis at the municipal level.

In addition, the exploratory analysis would be completely different, because it would consider a level of aggregation of the number of animals considerably lower than the total number of animals in a municipality. This would directly affect the proportion of the herd that could be affected by the animal in transit. It would also dramatically alter the diffusion curves, making them significantly smoother. It would take a much longer period of time to reach 100% of the state's municipalities, as animal flows would be much more dispersed. This is the major limitation of the current study, caused by the lack of access to more detailed data.

It is known that official databases do not cover 100% of the flow of animals within the country. In fact, there are studies that seek to estimate how much animal movement occurs outside the official records, like Correr et al. (41), who estimated that almost 10% of cattle traffic in Brazil has no official record. However, there are no means to track such movement nowadays and, therefore, the present study considered only the official data to construct the movement networks.

Papers in the veterinary field are usually based on farm-level data, with geographic information. The unavailability (for this study) of more disaggregated and geo-referenced data did not allow more complex analyzes. This reinforces the need for investments in animal movement control and in tools that allow easy localization of livestock within Brazilian territory—improving the capacity to respond to sanitary emergencies, and to reduce the impacts of eventual outbreaks.

In Brazil, this is particularly relevant because the country intends to submit its candidature to the status of free of FMD without vaccination and to do that, it will be necessary to phase out the vaccination campaigns in the next few years. The possible impacts of a FMD reintroduction in the country would certainly be more dramatic if the herd is not immunized anymore—given that in an important state in cattle farming, such as MS, the animal movement networks are strongly connected and present municipalities with significant animal flows.

Thus, it is essential to assure that, before removing the vaccination, the states' animal health services as well as the federal service are ready to enhance the level of security by inspection and monitoring as well as by an efficient system of intelligence that would allow for a quick response in case of an outbreak.

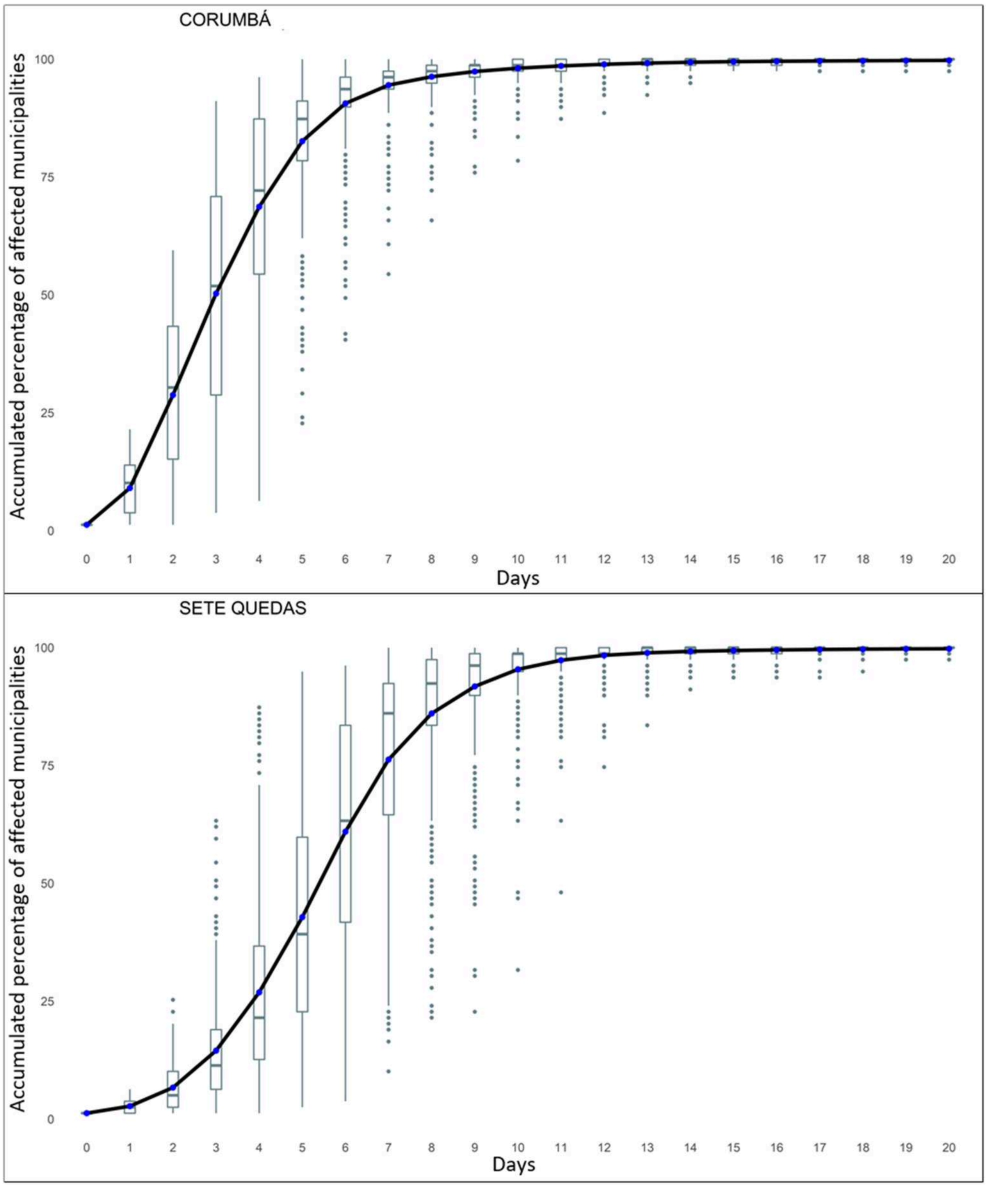

FIGURE 12 | Diffusion curves for animal movements within Mato Grosso do Sul initiated in Corumbá and Sete Quedas. Source: Elaborated from GTAs. Note: Number of affected municipalities per day distributed in quartiles (boxplot). The blue dots represent the average of the distributions and were interconnected to form the accumulated average curves.

For that, it is important to consider municipalities (or farms) that concentrate many animals and animal flows—those that are more central in the movement networks.

Other factors can be considered, so we can build a model for the disease transmission in Brazil, such as: number of animals transported; number of animals passing through the border without inspection; other susceptible species; movement of animal products; FMD transmission rate; effective vaccination rate; effectiveness of sanitary inspection, inside and outside the farms. Ideally, Brazil should have at least one model for the FMD virus spread, such as AusSpread in Australia (42) and NAASDM in United States (43), to assist in the formulation of public policies, allocation of resources, and development of an outbreak response plan. In the meantime, studies like this seek to promote discussions and assist policy makers in order to contribute to the development of Brazilian livestock.

CONCLUSIONS

This characterization and exploratory analysis of cattle movement between municipalities of Mato Grosso do Sul State

(MS, Brazil) identifies the regions and periods of higher animal flow density and, therefore, periods in which all municipalities of the state are in a situation of greater vulnerability.

Cattle movement networks within the state demonstrated to strongly connect municipalities. This implies a high-speed potential of FMD transmission in the state. As MS sends animals to other Brazilian states, the outbreak could spread to other locations in the country. The greater the infected area, the greater the economic impacts of the disease, which include everything from control and containment of the outbreak, to market losses and reduction in beef prices—impacting the whole livestock chain and all the other sectors of the economy interconnected with it.

The analysis demonstrates the need and importance of investing in animal control, sanitary education for producers and equipment and technologies to assist in the early detection, diagnosis, and eradication of outbreaks in a fast and efficient manner, preventing a possible outbreak from spreading to other regions.

The scarcity of studies on this subject makes this exercise an initial step toward further developments in order to explore a matter of such importance for the state and for the Brazilian economy as a whole. In future research, machine learning and big data tools could be exploited to improve the analysis, in order to generate scenarios as tools for police markers. All limitations of this work were conveyed to the decision makers at the end of the project.

Despite the history of crises and the significant portion of domestic exports affected, the economic impacts of FMD in Brazil are still poorly understood. Further studies, based on detailed data and the application of robust economic models, based upon epidemiological models, should be promoted in order to accurately measure the risks and impacts of the disease in the country, and thus improve decision-making regarding sanitary actions and animal health protection.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

AUTHOR CONTRIBUTIONS

TM was guided by the professors during the master's degree and this article is derived from the dissertation. SM contributed to the analyzes of Brazilian livestock and foot-and-mouth disease. IL contributed to the methodology of analysis of socioeconomic networks.

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Effects of Drought and Media-Reported Violence on Cattle Fever Tick Incursions

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Ectoparasites, such as cattle fever ticks, and the diseases they carry pose a risk to the global cattle population in reduced productivity and in livability. Tick infestations carry significant economic implications through losses in productivity, increased morbidity, and control costs. Cattle fever ticks were eradicated from the United States through concentrated efforts across state and federal agencies. The Cattle Fever Tick Eradication Program maintains a permanent quarantine and buffer zone along the Texas-Mexico border to monitor and control reincursions of the tick from Mexico due to movements of wildlife or stray animals. The number of apprehensions of stray livestock and changing infestation rates may be influenced by many factors including increases in violence along the border or environmental effects such as weather pattern changes, river levels, or temperature fluctuations. Using annual records of the number of cattle apprehended and infestation rates, an analysis of the effects of media-reported border violence and environmental conditions can provide a unique understanding of cattle fever tick prevention and the challenges control programs face. Results from this analysis suggest that both media-reported violence and weather changes affect the rate at which infested cattle are apprehended, and these effects differ depending on spatial and temporal factors. With continued land use changes, social unrest in endemic areas, and changing weather patterns, the efforts to control and eradicate cattle fever ticks, both in the United States and globally, is likely to be an ongoing concern.

Keywords: cattle fever ticks, tick control, environmental conditions, drought, media-reported violence, border violence

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INTRODUCTION

Cattle fever ticks (*Rhipicephalus microplus* and *Rhipicephalus annulatus*) (CFT) are species of ticks that can carry parasites such as *Babesia bigemina* or *Babesia bovis* which causes the protozoal disease babesiosis, commonly called cattle fever in the United States (US) or tick fever in other countries. Cattle fever leads to anemia, reduced milk production, loss of weight, increased morbidity and even mortality in infected cattle that are left untreated. These ticks pose a threat to the 1.5 billion cattle globally, especially in tropical areas where the host tick densities are the highest. For US cattle,

cattle fever was once a significant animal health epidemic, but through concerted efforts by livestock producers as well as federal and state agencies, the tick vector has been successfully eradicated, and a permanent quarantine area has been established to monitor for reincursions from Mexico where the tick is endemic (1–3). The Cattle Fever Tick Eradication Program (CFTEP) continues to support efforts to ensure the health and well-being of U.S. cattle through vigilant surveillance and response to fever tick incursions.

According to the Texas Department of Transportation, Texas and Mexico share 1,254 miles of border with 28 international bridges and crossing points, which include a hand-drawn ferry, numerous dams, rail-only, and other crossings (4). The border is defined by the route of the Rio Grande River, the fifth longest river in the US and among the top 20 in the world (About the Rio Grande[1]). The border between the US and Mexico is highly trafficked with over 33 million personal vehicles and 17 million pedestrians crossing Northbound in single year (5). The Permanent Cattle Fever Tick Quarantine zone (PQZ) traverses nearly 580 miles along this border and ranges from 125 yards to nearly 8 miles wide (see **Figure 1**). The PQZ includes areas of nine south Texas counties: Cameron, Dimmit, Hidalgo, Kinney, Maverick, Starr, Val Verde, Webb, and Zapata. Within the PQZ, livestock producers are required to treat their cattle for ticks, using large dipping vats, spray treatments, or injectable treatments all monitored by USDA and Texas Animal Health Commission (TAHC). Patrolling along the Texas/Mexico border are mounted riders, more familiarly called tick riders, which intercept stray livestock moving across the border. These livestock are checked for ticks, treated, and returned to their owners where possible.

There are many factors that could contribute to changes in the frequency of incursions of cattle fever ticks. Suitable tick environments in terms of host, vegetation, and climate along both sides of the border and extreme weather patterns can cause push and pull effects for ticks as well as for their hosts–cattle and wildlife. Increases in the number of stray animals from Mexico due to economic or regional instability due to violence can lead to increased introductory pressures as farms are abandoned and animals left to fend for themselves. Using data collected from the CFTEP, an analysis of the factors that contribute to cattle fever tick incursions and infestation rates was conducted with a focus on the implications of border violence and environmental effects.

BACKGROUND

When first identified, CFT were believed to only infest cattle, but they have been found on a variety of domesticated animals including equids, as well as, wild animals such as white tail deer (*Odocoileus virginianus*), red deer (*Cervus elaphus*), and the invasive nilgai antelope (*Boselaphus tragocamelus*) (5, 7–9). This broad range of free-moving hosts poses unique challenges for surveillance and management of incursions within the PQZ, with changes in host densities possibly leading to increased infestations. Pound et al. (10) showed that increases in densities of white-tailed deer in southern Texas and northern Mexico led to increases in the number of CFT infestations in the US. Eradication of CFT in 14 states of the southeastern US and southern California was achieved by 1943, but total eradication from the US was delayed by the persistence of CFT on deer populations in southern Texas and Florida (8). In addition to mounted patrols, the CFTEP also treats products from deer harvested in the PQZ to ensure CFT are not taken out of the zone. As for controlling CFT, infested cattle are dipped in organophosphates, while deer populations are treated seasonally, February through July, through 1,500–2,000 feeding stations of ivermectin treated corn annually to reduce tick infestations (10–12). However, continued containment of CFT within this high risk region has been challenged by increases in tick resistance to acaricides in Mexico and Texas, movement of sylvatic hosts, such as white tail deer back and forth across the border, and incursions of ticks into U.S. Fish and Wildlife Services Refuges, where treatment or mitigation is extremely difficult, leading to a need for more directed control measures and innovations in control of CFT (5, 13, 14). Alternatives currently in use include resistant cattle selection and exploration of novel chemical and biological controls (15, 16).

While successful, the eradication of CFT in the US has been costly—costs totaling more than $3 billion in today's dollars—and a broad scale reintroduction could be devastating to the US cattle industry in terms of animal health and welfare, leading to costs upward of $1 billion annually (11). This estimated cost of reintroduction includes the cost of tick control (labor, treatments, and opportunity losses of capital associated with control) in addition to the losses in production due to morbidity in beef cattle and milk production losses in dairy cattle, if not leading to widespread mortality, as well as the effects on consumer prices and welfare (17). Co-morbidity would also be a concern, with CFT infestations further exacerbating animal health conditions. Given the severity of the consequences resulting from re-establishment of CFT in the U.S. outside of the PQZ, constant surveillance and effective control in the PQZ is of paramount importance in reducing the risk of reintroduction of CFT to the US.

Cattle Fever Tick Habitation

While the CFT's hosts may be varied, optimal tick habitats influence the spread and establishment of CFT populations. As a highly adaptable species, CFT are established in tropical and subtropical regions throughout the world (8). In North America, these ticks are endemic only in Mexico, where optimal tick habitat support infestations of 65% of the country with *R. microplus* (13, 18). However, evidence shows that the different CFT species do not have the same optimal habitation. Lohmeyer et al. (19) used data collected on CFT infestations and distributional mapping to provide evidence of a parapatric boundary between the two CFT species. This biogeographical boundary could be a result of environmental factors, genetics, or some combination of the two, but the distinction may provide an indicator of the species of ticks most likely to occur in different areas of the PQZ.

[1] About the Rio Grande Ibwc.gov. Available online at: https://www.ibwc.gov/CRP/riogrande.htm (accessed May 26, 2020).

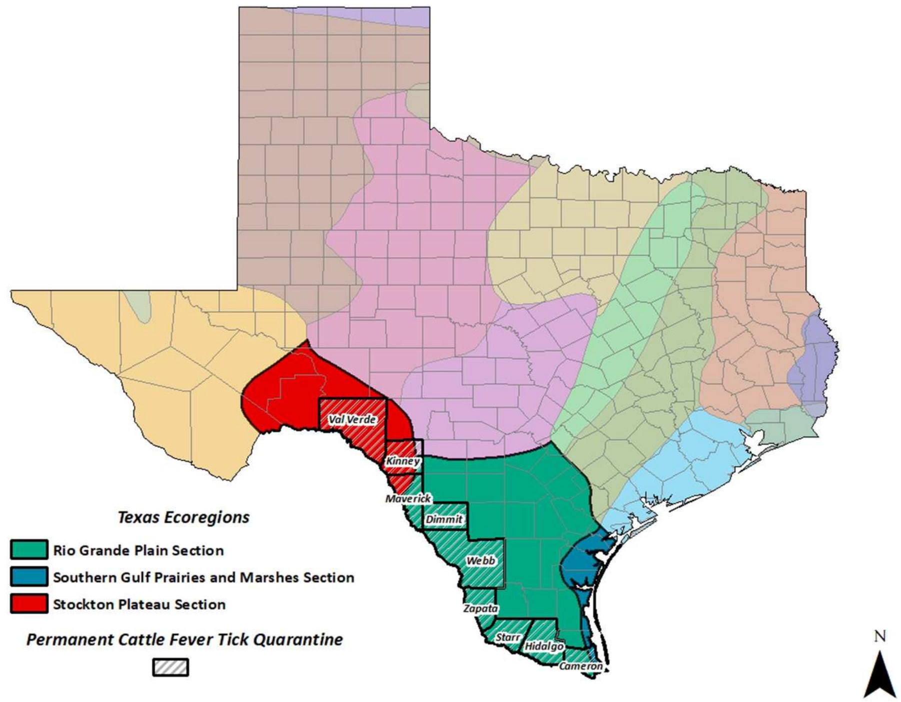

FIGURE 1 | Permanent Cattle Fever Tick Quarantine and Ecoregions of Texas Described by Bailey (6).

Like many vectors, ticks are susceptible to changes in climate and ecosystems (20). The spread, seasonality, and abundance of CFT are likely affected by climate traits among many other complex factors, and these influences may also have an effect on transmission risk (20). Giles et al. (5) modeled the range expansions of CFT given changes in weather patterns, and predicted increased pressures on the southeast United States, not through cattle movements alone but through changes in optimal tick habitats. The most suitable range for these ticks is currently in Texas and California, but researchers' models suggest expansion of this range into New Mexico and Arizona, with Louisiana, Oklahoma, Arkansas, Mississippi, Alabama, Georgia, and Florida as moderately suitable habitats (5). This expanded range would be consistent with historical tick population in the United States. Changes in weather conditions are likely to influence host population dynamics and the patterns of CFT persistence in the PQZ over time, leading to temporal or spatial shifts in tick incursions and establishment in the PQZ.

Human Influences on Cattle Fever Ticks

Similar to climate, human directed ecosystem changes can lead to instability and changes in tick habitation and pest pressure. Ecosystem changes include land use, urbanization and urban encroachment of habitats, habitat fragmentation, land divisions, changes in vegetation, along with many other human directed causes (5, 21). In addition to the changes in tick habitats, human directed ecosystem changes can also drive CFT host movements. For example, production intensification of export-destined cattle in the three Mexican states which border the PQZ—Coahuila, Nuevo Leon, and Tamaulipas which make up 33.24% of Mexico's cattle exports—can lead to increased risks for Mexican cattle escaping enclosures or breaking free from a larger herd and crossing the border carrying CFT (13, 22). During drought periods, ranchers may move their animals closer to rivers in search of green forage, which can provide access for river crossings. Additionally, backyard "traspatio" cattle are at risk of becoming lost or stray during distressing periods, such as droughts, financial hardships reducing investment and maintenance of farm infrastructure, or periods of violence leading to farm abandonment. Farm abandonment can be caused by financial, physical, or emotional distress both on producers and the local economies (23). Some criminal activities can lead to farm abandonment through fear and unrest (24). Understanding how human mediated pressures on CFT and tick hosts move into the PQZ can lead to improved planning during these events.

MATERIALS AND METHODS

Data

The data used in this analysis were collected from various sources. Annual cattle apprehension data were recorded by CFTEP personnel and tick riders from 1975 to 2019[2] for the nine

[2]The year 2014 is excluded from the analysis as it represents outlier period where ∼200 cattle were requested to be moved by the CFTEP. However, these cattle had lived in the northern part of the PQZ (an area not environmentally optimal for tick development) for more than a decade and does not represent cattle apprehended and checked for cattle fever ticks in the course of normal operations.

counties in the PQZ. This data included the total number of cattle apprehended, the number of infested and non-infested cattle, and the county where the cattle were apprehended. Due to limited apprehensions, Kinney and Dimmit counties were dropped from all empirical models. These counties, while technically in the PQZ, have very little of the county abutting the border with Mexico. For the purposes of this analysis, we were interested in the changes in the number of infested cattle (*InfestedCattle*) over time. Overall trends visualized in **Figure 2**, show an increase in cattle apprehended and an increase in infestation rates over the time period examined. The factors studied in this analysis aim to explain this variability in the apprehensions and infestations over time.

Apprehensions are a function of the quantity and quality of tick riders that scout, track, and apprehend stray cattle throughout the PQZ. In order to capture the fluctuation of available labor, the number (in thousands) of horseback patrol hours (*RiverPatrolHours*) was collected from the CFTEP. The use of tick rider patrol hours accounts for overall patrol counts as well as the various number of tick riders for any given period. Annual patrol hours were only available in aggregate from 1990 to 2019 for the entire PQZ, so county specific hours could not be used.

Violence and violent activities can lead to increased farm abandonment and potentially reduced animal management activity, leaving stray cattle free to roam. In order to examine this effect, violent activity was collected using a media index for search terms related to border violence adjacent to the PQZ. An overall media index was calculated (*MediaAvg*) by averaging and re-indexing indices collected for the study region of various search terms related border violence, drug cartel violence, and Mexican drug cartel activities. These indices were gathered from Google Trends, a free online resource which captures the importance of a search or news topic for a given geography over time (25). In order to assess how well the Google Trends index reflected violent activity, we obtained a dataset from the Uppsala Conflict Data Program (26) that collects some records of violent activity (generally only activities that result in human deaths). A correlation of the media index with the available data series showed that *MediaAvg* was highly correlated (0.89) with the best death estimates available. The media trends provide an indication of the overall levels of violent activity, not just those that lead to deaths or hospitalizations, which serve as a better proxy for possible events influencing cattle abandonment. The media indices were collected from 2004 to 2019, which encompasses the full data available from Google.

To account for environmental factors that may lead to increase in stray cattle movements or changes in optimal tick habitation, weather data were collected from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (27). This data included hydrological and ambient data, such at maximum temperatures (*TempMax*) and precipitation indices (*PCP*). Drought indices can relate similar information through subtle calculation variations (28). For this analysis, the precipitation index most directly related to river levels in the Rio Grande River, a reduction of which may lead to easier crossing

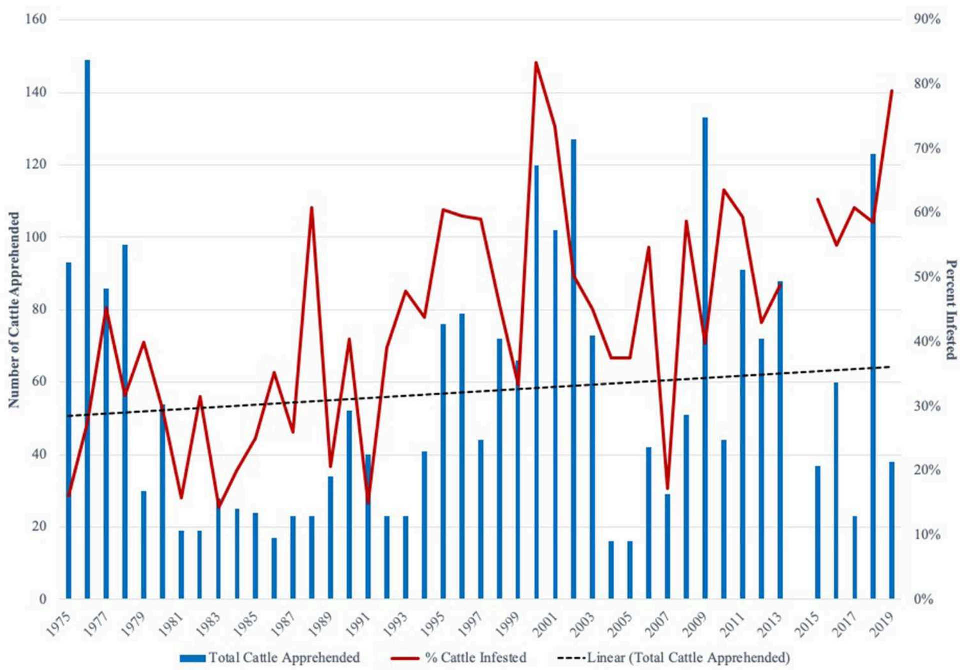

FIGURE 2 | Total cattle apprehended along Texas-Mexico Border and percent of cattle infested with Cattle Fever Ticks from 1975 to 2019*. *2014 excluded from figure as it represents outlier period where 200 cattle which had lived in the Permanent Cattle Fever Tick Quarantine Area for more than a decade were requested to be moved by the Cattle Fever Tick Eradication Program and does not represent cattle apprehended and checked for cattle fever ticks.

for livestock. The intention was to capture both the push and pull effects of environmental changes on cattle fever ticks and their hosts. Temperature extremes may explain livestock movements toward better grazing, while precipitation allows the effects of precipitation on river levels and forage growth to be modeled across the study region.

In order to capture the biogeographical CFT pressures, ecoregions were defined for the nine-county study region (**Figure 1**). The ecoregions identified in the PQZ were: Rio Grande Plains, Southern Gulf Prairies and Marshes, and Stockton Plateau as defined by Bailey (6). Where ecoregions overlapped in a county, the ecoregion that predominantly covered the county was recorded, leading to Southern Gulf ecoregion not being included despite covering part of Cameron County. While it would have been more accurate to record two ecoregions, this led to indicators representing individual counties rather than tick habitat suitability across counties. For the purposes of the analysis, Rio Grande Plains was considered the baseline and excluded to avoid multicollinearity.

An overall trend variable (*Trend*) was included to capture temporal changes in annual cattle and tick movements not associated with the previous variables. A conceptual model is presented in **Figure 3** which shows the directed relationship of the variables on infested cattle apprehensions.

Methods

A panel modeling framework was used to determine the factors that contribute to CFT movements through infested cattle apprehensions. The panel nature of the by-county data over the study period provided a framework to estimate not only the effects across counties, but to best capture the temporal relationships between error terms. Due to the limiting nature of the media index and patrol hours, two sets of models were estimated. The first model group used the full set of explanatory variables and, empirically, the baseline model is represented in Equation (1):

$$InfestedBovine_{k,t} = \beta_1 + \beta_2 TempMax_{k,t} + \beta_3 PCP_{k,t} + \beta_4 MediaAvg_t + \beta_5 Trend_t + \beta_6 RiverPatrolHours_t + \gamma \, \mathrm{EcoRegion}_{k,t} + \varepsilon_{k,t} \quad (1)$$

where β_i and γ_i represent parameters to be estimated, variables are as defined above for the kth county in time t, and ε represents the estimated error term. The first set of models (*All Effects Models)* are limited in study period from 2004 to 2019. In order to better understand the possible interactive effects of violence, tick habitat, and weather, a series of nuanced models were also estimated to examine first-order interactions for all predictors in the model.

In order to fully understand the longer-term effects of weather, a second set of models, *Long-Term Effects Models*, were estimated using the full 1978–2019 data. Similarly, the first order interaction models were also estimated. The baseline model to estimate the effects of weather on infestation counts over time is shown in Equation (2):

$$InfestedBovine_{k,t} = \beta_1 + \beta_2 TempMax_{k,t} + \beta_3 PCP_{k,t} + \beta_5 Trend_t + \gamma EcoRegion_{k,t} + \varepsilon_{k,t} \quad (2)$$

where all variables and parameters are the same as previously defined.

In estimating the empirical models, the panel Poisson estimator was used to better handle distinct, non-negative count data over the traditional ordinary least squares approach, which would treat *InfestedCattle* as a continuous variable, leading to less efficient results. The Poisson estimator is a pseudo maximum likelihood model with a log likelihood of Equation (2):

$$\log L\,(\theta|X, Y) = \sum_{k=1}^{K} (y_{k,t}\theta x_{k,t} - e^{\theta' x_{k,t}} - \ln(y_{k,t}!)) \quad (3)$$

where θ represents the set of parameters and $y_{k,t}$ and $x_{k,t}$ represent the observed counts and independent variables, respectively, for county k in year t. Optimal values of θ were determined through a search process of the pseudo-loglikelihood estimation.

One potential limitation of the Poisson estimator is that it makes an equidispersion assumption, which assumes the mean and variance are equal. If this assumption does not hold through overdispersion, a more generalized model, the negative binomial regression model, can be used. In order to test for overdispersion and to select the most appropriate model, a loglikelihood ratio test was estimated. Results failed to reject the hypothesis for equidispersion of mean and variance, thus confirming the appropriateness of the use of the Poisson estimator over a more generalized count estimator. Additionally, robust standard errors, clustering by county, were used for this analysis which helped to guard against underestimations of the error terms, a concern with Poisson estimators, as well as to address potential serial correlation in these terms.

RESULTS AND DISCUSSION

A summary of the CFT data at the county level is presented in **Table 1** with a total of 286 county-level annual observations. Overall, there were 2,090 cattle apprehended over the time frame with an average of seven cattle (both non-infested and infested) apprehended in any given county per year, but this varies substantially with up to 70 non-infested and 64 infested cattle apprehended. As shown in **Figure 1**, the overlay of ecoregions on the counties in Texas shows much of the PQZ are centered in the Rio Grande Ecoregion. County-level infestation counts are presented in **Table 2**, note that Kinney county had no cattle apprehended, and Dimmit has limited observations with only one infested cow apprehended during the study periods due to their limited PQZ border area. As a result, these counties were excluded from the analysis, as previously

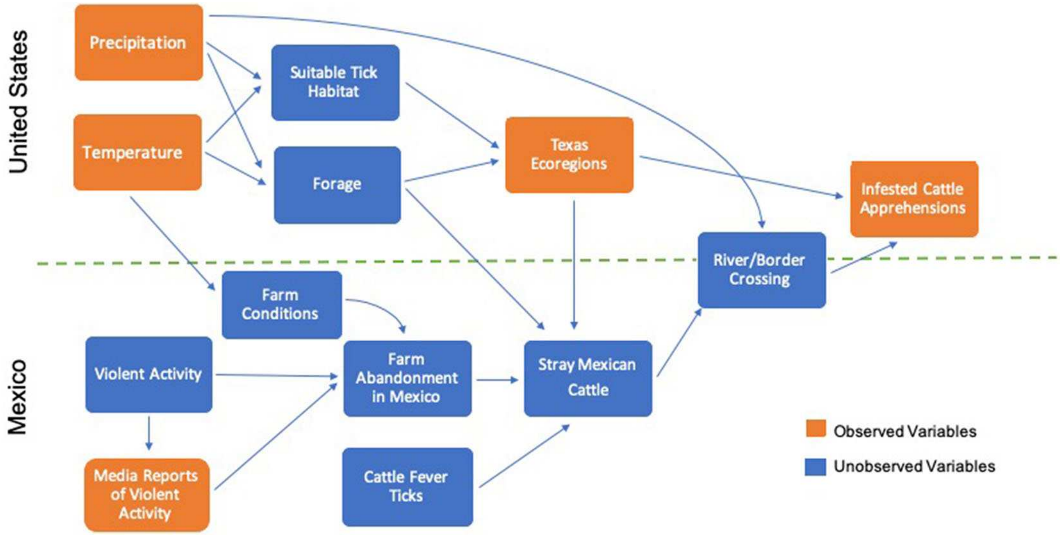

FIGURE 3 | Conceptual model of directed relationships in Cattle Fever Tick analysis.

TABLE 1 | Summary statistics for Cattle Fever Tick county-level annual data 1978–2019[a,b].

Variable	Units	*N*	Mean	Std. dev.	Min	Max
Non-infested cattle	Count of cattle	286	3.7	7.4	0	70
Infested cattle	Count of cattle	286	3.6	7.8	0	64
Percent infested	Percent	286	36	41	0	100
River Patrol Hours[c]	Thousands of annual patrol hours for all counties	202	23.36	6.84	6.95	31.89
PCP	Precipitation index	286	1.95	0.45	0.93	3.05
Temp Max	Temperature (F)	286	83.85	1.53	81.18	87.28
Media average[d]	Index	104	44.75	23.91	10.75	100
Ecoregion: Rio Grande	1 if county in Ecoregion; 0 otherwise	286	0.72	0.34	0	1
Ecoregion: Stockton Plateau	1 if county in Ecoregion; 0 otherwise	286	0.28	0.45	0	1

[a] *Excluding Dimmit and Kinney counties.*
[b] *These summary statistics are derived from annual summaries for each county, as such the min and max represent the highest or lowest single annual county value, across all counties.*
[c] *Annual river patrol hours are limited to 1990–2019.*
[d] *Annual media index is limited to 2004–2019.*

discussed. There are counties that have a higher concentration of infested cattle apprehended, such as Val Verde, which on average has 10.5 infested cattle apprehended annually (max 64) compared to Zapata with 1 infested cow on average apprehended annually (max 9).

Selected modeling results are presented in **Tables 3**, **4**. The incident rate ratios (IRR) represent the exponentiated coefficients and express the factor that the expected count of infested cattle apprehended change given a unit change in the independent variable. Both tables include baseline models, select first-order interaction models, and a combined, all interactions model, which presents interactions that are both theoretically sound and contribute to the understanding of the predictors influence on variability in infested cattle apprehensions.

All Effects Model Discussion

For the *All Effects Models*, which was limited to 2004–2019 due to data availability, river patrol hours, media-reported violence, and tick habitability were all significant predictors, and the results are discussed individually below. The *Temp Max, PCP,* and *Year* variables were not significant in the baseline model. These weather variables may not have been significant due to the relatively short timeframe covered in these models, which would impact the ability to measure how weather might drive changes in habitat suitability and tick/host migratory patterns. Despite this, temperature did show an effect on apprehensions when related to media-reported violence. In the All Interactions model, the interaction between *Media Average* and *Temp Max* is estimated to affect infested cattle apprehensions by a factor of 1.01, which implies that the effects of media-reported violence differ given the temperature. In the *Long-Term Effects Model*s presented later, the change in temperature and an overall trend shows a significant relationship across all models. The exact reason is unknown but these results may indicate a relationship between temperature and ranching conditions that may induce livestock to stray, such as drought conditions (e.g., low rainfall and high temperatures) or shorter-term shortages in forage, hay, or water.

TABLE 2 | Annual county infested cattle apprehension summary 1979–2019.

County	*N*	Mean	Std. dev.	Min	Max
Cameron	41	2.1	3.5	0	18
Dimmit	12	0.2	0.4	0	1
Hidalgo	41	1.0	2.4	0	12
Kinney	13	0.0	0.0	0	0
Maverick	41	5.0	8.6	0	30
Starr	41	2.3	4.0	0	19
Val Verde	40	10.5	15.4	0	64
Webb	41	3.5	5.4	0	27
Zapata	41	1.0	2.0	0	9
Total[a]	286	3.4	7.7	0	64

[a] *Excluding Dimmit and Kinney.*

Patrol Hours (*River Patrol Hours*) was a significant predictor in all models. While the average number of patrol hours in the dataset was 23,000 h/year, for every additional 1,000 h of patrol annually, the likelihood of additional counts of infested cattle increases by 4–7% (**Table 3**). This implies that the number of hours patrolled has a significant effect on capturing infested cattle. In estimating all first-order interaction, the effect of patrol hours varied significantly ($p < 0.01$) with weather variables (*Temp Max* or *PCP*) or with *Year* (not presented in **Table 3**); however, both interactions could not be combined into a single model due to collinearity issues. However, these results suggest that the relationship between river patrol hours and infested cattle apprehensions may be impacted by climate variability. The relationship between climate variability and river patrol hours also increases the impact of the river patrol hours meaning that during periods of increased climate variability an increase in river patrol hours can compensate for this volatility.

Thinking about these results in another way, model results show that reducing the number of patrol hours would directly reduce the number of infested cattle apprehended, which may lead to reinfestations, high (nearly 90%) mortality rates, and high control costs (5). Recognizing the value of tick rider patrol hours is useful in understanding the effectiveness and importance of the horseback patrols and the financial support of vigilant surveillance in the PQZ.

Like river patrol hours, the media-reported violence indices showed a significant effect ($p < 0.1$ and $p < 0.05$) in the baseline and interacted models. During times of increased media reporting of violence and violent activities in the PQZ, the likelihood of infested cattle apprehensions increases. For example, using the baseline model, an increase by one point in the media index increases infested apprehensions by 1%. For the *All Interactions* model, media-reported violence appears to vary based on location (ecoregion) and temperature. While the mechanisms for these effects are not clear based on the available data, it is possible that periods of intense violence and violent activities could lead to an increase in farm or cattle abandonment leading to increased stray animals. The significant effect of media-reported violence and violent activities on farm abandonment reinforces the literature in the broad effects of social and political conflicts outlined by Maldonado Aranda (23) and Deraga (24). In addition to farm abandonment, cattle may be triggered to move due to violent or loud, disruptive activity in their home ranges. The relationship between media-reported violence and infected cattle apprehensions highlights the need for further sociologic work in this region, which may provide a more complete understanding of the driving forces behind CFT pressures in the PQZ.

The largest influencing factor on CFT apprehensions was tick habitability. There are significant ($p < 0.01$) differences in ecoregion-estimated apprehension counts across the baseline and interacted models for the Rio Grande and Stockton Plateau ecoregions. Stockton Plateau ecoregion is expected to have 5.11 times greater rate of infested cattle apprehensions than Rio Grande ecoregion in the baseline model. Additionally, the effect of ecoregion appears to vary based on media-reported violence, such that there is a significant ($p < 0.01$) difference in the effects, a factor of 1.03 for the Stockton Plateau over the Rio Grande ecoregion, of media reported violence and violent activity by ecoregions. This variability could indicate either heterogeneity in the location of violent activities or that the movement patterns of stray animals have some preference during times of high stress, such as abandonment. The difference in apprehension rates is interesting, since the ecoregions vary in terms of accessibility, visibility, and desirability of hosts moving across the border. A combined understanding of where infested cattle are more likely to enter into the PQZ and where tick habitat and host availability is most likely to allow establishment of the tick could be used to prioritize labor or resources during emergencies, such as outbreaks of other diseases, that may draw resources to other areas.

Long-Term Effects Model Discussion

The *All Effects Models* provide an understanding of a broader set of explanatory factors that may contribute to tick infestations and apprehensions, but they are limited to a smaller sample of data. In order to understand the long-term effects of weather changes on infested cattle apprehensions, the *Long-Term Effects Model* was estimated. Directionally, the results are consistent with the previous model; however, this model has the benefit of estimating the overarching effects of the climate as well as temporal and spatial effects. Results are shown in **Table 4**.

In terms of temperature, the *Long-Term Effects Models* shows a significant effect ($p < 0.05$–0.01), such that for every one degree increase in the average maximum temperature by county, the number of cattle apprehended is 16% greater than the expected counts. This change in apprehension shows that over the full data series, weather could be driving changing patterns of livestock movement or changes in tick habitat suitability. These results provide additional indication of the effects of changing weather patterns on tick habitats that was discussed in the literature by Estrada-Peña (20). Additionally, the effects of weather are not uniform across all regions. When accounting for the effects of temperature across the entire time frame, within the Stockton Plateau ecoregion, there is a 1.30–1.20 times greater rate in the number of infested cattle apprehended compared to the Rio Grande ecoregion ($p < 0.01$). These regional, climactic effects suggest that weather changes may affect tick habitat suitability

TABLE 3 | Incident rate ratio results for all effects models on Cattle Fever Tick infestation counts of apprehended cattle through the Cattle Fever Tick Eradication Program 2004–2019.

	Baseline	Media interaction with ecoregion	PCP interaction with year	All interactions
River Patrol Hours (thousands)	1.04**	1.05***	1.07*	1.07*
	(0.02)	(0.02)	(0.04)	(0.04)
Temp Max	1.18	1.15	1.32***	1.07
	(0.14)	(0.15)	(0.13)	(0.16)
Media average	1.01*	0.99	1.02**	0.66*
	(0.01)	(0.01)	(0.01)	(0.15)
Media average × Ecoregion: Stockton Plateau		1.03***		1.03***
		(0.01)		(0.00)
Media average × Temp Max				1.01*
				(0.00)
PCP × Year			1.32**	1.32
			(0.17)	(0.15)
PCP	1.23	1.12	0.00**	0.00**
	(0.95)	(0.89)	(0.00)	(0.00)
Year	1.13	1.15***	0.67*	0.67*
	(0.05)	(0.06)	(0.16)	(0.14)
Ecoregion: Stockton Plateau	5.11***	1.14	5.27***	1.00
	(0.01)	(0.70)	(1.73)	(0.67)
Constant	0.00***	0.00***	0.00*	0.00***
	(19.66)	(0.00)	(0.00)	(0.00)
Log Pseudolikelihood	−432.87	−413.19	−406.23	−380.19
N	104	104	104	104
Groups[2]	7	7	7	7
Mean *N* per Group	14.9	14.9	14.9	14.9

*Results are incident rate ratios (IRR); *p < 0.1; **p < 0.05; and ***p < 0.01, Robust standard errors are in parentheses. Includes all quarantined counties except Dimmit and Kinney.*

TABLE 4 | Incident rate ratio results long-term effects models on Cattle Fever Tick infestation counts of apprehended cattle through the Cattle Fever Tick Eradication Program 1978–2019.

	Baseline	Region interaction with temp max	Region interaction with year	All interactions
Temp Max	1.16**	0.99	1.16**	1.02
	(0.06)	(0.11)	(0.07)	(0.05)
PCP	0.96	0.95	0.94	0.94
	(0.32)	(0.30)	(0.30)	(0.10)
Year	1.03**	1.03**	1.01	1.02***
	(0.01)	(0.01)	(0.01)	(0.01)
Ecoregion: Stockton Plateau	4.08***	0.00***	0.00**	0.00***
	(0.34)	(0.00)	(0.00)	(0.00)
Ecoregion: Stockton Plateau × Temp Max		1.30***		1.20***
		(0.09)		(0.06)
Ecoregion: Stockton Plateau × Year			1.03***	1.02***
			(0.13)	(0.06)
Constant	0.00***	0.00***	0.00	0.00***
	(19.66)	(0.00)	0.00	(0.00)
Log Pseudolikelihood	−1,169	−1,149	−1,152	−1,145
N	286	286	286	286
Groups[2]	7	7	7	7
Mean *N* per group	40.9	40.9	40.9	40.9

*Results are incident rate ratios (IRR); *p < 0.1; **p < 0.05; and ***p < 0.01, Robust standard errors are in parentheses. Includes all quarantined counties except Dimmit and Kinney.*

and these changes are unlikely to be homogenous across the region. This may require ecoregion-specific approaches to dealing with weather patterns deviations within the PQZ.

The ecoregion-estimated IRRs for the *Long-Term Models*, while consistent with the results of the *All Effects Models*, are slightly more conservative. In the baseline model, Stockton Plateau ecoregion had an infested cattle apprehension rate 4.08 times higher, compared to the Rio Grande ecoregion. Building on the previous discussion, the effect of ecoregion also varies by year. Ecoregion-year interactions indicate a 1.02–1.03 increase in infested cattle apprehensions for Stockton Plateau for each an additional year. This slope adjustment implies that in addition to weather changes varying by region, temporal changes also vary by region, which speaks to the heterogeneity of counties within the PQZ. An explanation for these temporal effects could be heterogenous land use and management changes over time within ecoregions. Overall, these results reassert the importance of understanding how and where infested cattle introductions change over time, as well as understanding the complex interactions of weather and ecoregion-specific factors on the success of apprehensions.

Following the temporal changes by ecoregion, there was a significant estimated annual change in infested cattle apprehensions over the study period. For each additional year, counts of infested cattle apprehended is estimated to increase by 2–3% across all models. The long-term increase in infested cattle movements over time is consistent with continued pest pressures, reaffirming the value of the PQZ activities in monitoring for reincursions. These estimated effects are more conservative than in the *All Effects Models* (13% increase), which may indicate changes in PQZ management practices over time or may show an increased pressure of infested cattle during the previous 15 years vs. the entire 41-year period examined in the long-term effects model. Further research into tick management in endemic areas and habitats may shed more light on the causative factors associated with these increases.

CONCLUSIONS

Ectoparasites, such as cattle fever ticks, and the diseases they carry pose a risk to the global cattle population in reduced productivity and in livability. Cattle fever, bovine babesiosis, was once endemic in US cattle, but the disease was eradicated through concerted and costly efforts across agencies and producer groups to eradicate the cattle fever tick. Reintroduction of this disease to the US cattle herd could lead to substantial mortality and costs in terms of containment, eradication, and effects on producers and consumers. A permanent quarantine area provides constant surveillance for reincursions from endemic areas to minimize those risks. However, these risks vary due to a variety of factors, leading to fluctuating pressures on tick and host migrations into the permanent quarantine area.

The number of infested cattle apprehended in the permanent quarantine area has increased over the last several decades. By analyzing factors that help explain the variability in the number of infested cattle apprehended, this analysis provides a better understanding of how pressures for tick reintroduction, in the form of infested cattle, have and continue to change. The results from this analysis suggest that both media-reported violence and weather changes are associated with the rate at which infested cattle are apprehended, and these effects differ depending on spatial and temporal factors. With continued land use changes, social unrest in endemic areas, and changing weather patterns, the efforts to control and eradicate CFT, both in the United States and globally, is likely to be an ongoing concern. Control efforts which take into account these factors in addition to host/parasite ecology may be more successful in long-term prevention of reestablishment of the cattle fever tick in the U.S.

Continued study on the value of apprehending infested cattle and the mitigation of the risks and costs associated with reincursions is vital. Additionally, an economic analysis on the value of maintaining a permanent quarantine could create a deeper understanding of CFT control programs and impacts. For the U.S. to continue to be successful in controlling CFT, multidisciplinary and targeted approaches will be needed to account for changing CFT pressures as well as new and evolving control measures.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available upon request but may be subject to USDA approvals. Requests to access these datasets should be directed to Jada Thompson, jthom207@UTK.edu and Hallie Hasel, hallie.s.hasel@usda.gov.

ETHICS STATEMENT

The manuscript data used are secondary data with no identifying information for humans or animals. We used surveillance data provided by USDA:APHIS and other publicly available datasets to run the statistical models. The surveillance data is collected as part of the ongoing USDA Cattle Fever Tick Eradication Program. As such there are no ethics review needed for this paper.

AUTHOR CONTRIBUTIONS

JT was the project leader, estimated the statistical models, and lead manuscript development. AD led effects modification analysis and contributed to manuscript development. HH compiled data, provided expert advice, and contributed to manuscript development. DB coordinated group communication and contributed to manuscript development. All the authors met the contribution requirements for authorship per the author guidelines.

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A Value Chain Approach to Characterize the Chicken Sub-sector in Pakistan

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The chicken industry of Pakistan is a major livestock sub-sector, playing a pivotal role in economic growth and rural development. This study aimed to characterize and map the structure of broiler and layer production systems, associated value chains, and chicken disease management in Pakistan. Qualitative data were collected in 23 key informant interviews and one focus group discussion on the types of production systems, inputs, outputs, value addition, market dynamics, and disease management. Quantitative data on proportions of commodity flows were also obtained. Value chain maps were generated to illustrate stakeholder groups and their linkages, as well as flows of birds and products. Thematic analysis was conducted to explain the functionality of the processes, governance, and disease management. Major chicken production systems were: (1) Environmentally controlled production (97–98%) and (2) Open-sided house production (2–3%). Broiler management systems were classified as (I) Independent broiler production; (II) Partially integrated broiler production; and (III) Fully integrated broiler production, accounting for 65–75, 15–20, and 10–15% of commercial broiler meat supply, respectively. The management systems for layers were classified as (I) Partially integrated layer production and (II) Independent layer production, accounting for 10 and 80–85% in the egg production, respectively. The share of backyard birds for meat and eggs was 10–15%. Independent, and integrated systems for chicken production could be categorized in terms of value chain management, dominance of actors, type of finished product and target customers involved. Integrated systems predominantly targeted high-income customers and used formal infrastructure. Numerous informal chains were identified in independent and some partially integrated systems, with middlemen playing a key role in the distribution of finished birds and eggs. Structural deficiencies in terms of poor farm management, lack of regulations for ensuring good farming practices and price fixing of products were key themes identified. Both private and public stakeholders were found to have essential roles in passive disease surveillance, strategy development and provision of health consultancies. This study provides a foundation for policy-makers and stakeholders to investigate disease transmission, its impact and control and the structural deficiencies identified could inform interventions to improve performance of the poultry sector in Pakistan.

Keywords: Pakistan, chickens, production systems, mapping, value chains

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INTRODUCTION

Chicken production is an important sub-sector of agriculture in Pakistan and plays a pivotal role in rural economic development. The estimated number of commercial chickens in the country in 2017 was 1,022 million birds with production of 17,083 million eggs and 1,270,000 tons of meat, providing direct and indirect employment to over 1.5 million people (1, 2). The commercial chicken industry in Pakistan has grown at 8–10% annually over the past two decades (3). The efficiency and availability of modern farming technologies, high profit margins, and the establishment of federal institutions for poultry production in the 1990s were important drivers for the modern chicken industry in Pakistan (4). The growth of the livestock industry in low and middle income countries is determined by a rise in the total number of livestock, whereas per animal carcass weight is the key indicator in high income countries (5). In 2015, Pakistan was the 11th largest chicken producer in the world on the basis of number of birds produced (2, 6). Since then, investment by private and public sectors has increased, from 200 billion Pakistani rupee (PKR) (1.28 billion USD) in 2015 to 700 billion PKR (4.47 billion USD) in 2018.

The initial rise (1960–1980) in growth of the chicken industry was promising but not sustained. Outbreaks of infectious diseases like hydropericardium syndrome, infectious bursal disease (4) and avian influenza (AI) (7) caused important production losses and trade embargos (8). This triggered a shift in the chicken production sector toward more industrial production with farmers relocating their poultry production units into cooler and more bio-secured hilly northern areas of Pakistan and switching to environmentally controlled houses (4).

Chicken meat accounts for 32.7% of the total meat production in Pakistan (2), 70% of which is produced in the Punjab province (3). Consumption of chicken meat is growing steadily in Pakistan because of its low price (beef is over 20% and mutton is over 50% more expensive) and low fat content (3, 9). It is also attractive to value chain actors because of a short production cycle and easier processing of carcasses due to being smaller size than alternative meats such as mutton and beef (3, 6). Despite this growth, the average chicken product consumption per capita in Pakistan, a low and middle income country, is 5 kilograms of meat and 51 eggs per annum, whereas in high income countries it is 40 kilograms of meat and 300 eggs annually (8). The current standing population of 1,560 million broilers and 60 million layers is still insufficient to meet local needs for meat and eggs (9). As more people are consuming halal (the prescribed method of slaughter under Islamic law) meat globally, there is also an opportunity for Pakistan to increase its halal chicken meat export across the world.

The poultry industry in Pakistan is constantly evolving supported by government in form of tax reliefs, passing of the Punjab Poultry Production Act (10) and development of appropriate slaughter houses (6). Its growth has offered opportunities for national and international investors. The rapidly growing population, along with the influx of people to urban areas, and changes in people's eating habits, are creating business opportunities for animal protein producers in Pakistan (11). Increases in the domestic price of red meat, due to its fluctuating local and export markets, drastic changes in local supply and demand, and economic instability of the country (12) are further driving developments in the chicken production sector. Increasing investments in the chicken production industry, along with the expansion of chicken sales networks, are responsible for the reduced prices of chicken and its products, making chicken meat and eggs some of the cheapest and most consumed sources of animal protein in the country (8).

There is a dearth of modern value chain tactics in the supply and marketing of chicken and its products (6) for most of the poultry produced in the country. Despite increased production, there is limited vertical integration. Structural inefficiencies in terms of fragmented broiler and layer production and weak institutional environments result in a lack of coordination in terms of production, pricing, and marketing decisions for chicken meat and eggs (13). These discrepancies are further potentiated by the lack of scientific, hygienic methods to process poultry meat and eggs at the retail level, and a scarcity of capacity in poultry meat bioscience and technology which could hinder future development of the industry (3).

Mapping of production systems can provide an overview and understanding of the various production, harvesting, and distribution steps, types of actors and products involved along with their hierarchal position in value chains (14). Furthermore, the analysis of livestock value chains develops understanding of the operations, structural inefficiencies and identification of critical points for potential policy interventions (15). Despite the growing poultry industry and its importance in providing affordable and healthy protein in form of meat and eggs, no study has yet mapped poultry value chains in Pakistan.

Chaudhry et al. (13) studied pricing mechanisms in commercial broiler value chains and found the industry at the brink of crisis due to strong price fluctuations. Jalil et al. (12) also studied meat value chains in smallholders in Pakistan and found large transportation costs that were responsible for high prices of red and white meat. Hence, there is a need to investigate the detailed structure of the broiler and layer value chains in order to understand and target the intervention points for disease and value chain management that can support economic resilience and food safety within these chains. This is of particular importance due to the presence of continuous fluctuations in the price of inputs for chicken farming and of infectious diseases like AI threatening the efficiency and safety of the system. Value chain studies have been recommended in the development of strategies to prevent and control AI, especially in East Asian countries (16, 17) and to measure disease and intervention effects in these systems.

The main aims of this study were to characterize and map the commercial broiler and layer production systems and the value chains associated with these systems and to investigate options for chicken disease management and reporting in different production systems in Pakistan. The outcomes of this study generate information relevant for stakeholders, directly and indirectly involved in chicken production, who could be interested in identifying ways to improve value chain operations and design efficient disease control strategies.

MATERIALS AND METHODS

Broiler, layer, and backyard chicken production systems and their value chains were studied by collecting qualitative and quantitative data between October 2017 and December 2017 mainly by key informant interviews (KIIs) and one focus group discussion (FGD). Activities included (a) identifying the various value chain systems; (b) investigating their contribution to the total meat and egg production in the country; (c) mapping and describing the meat and egg value chains of different broiler and layer production systems. The latter included characterizing types of stakeholders, products and flows in the value chains, and identifying the services and measures taken for diseases like AI prevention and control.

Study Area and Selection of Participants

Punjab province was selected as the study area, because it accounts for the highest share in broiler and layer production in Pakistan with 608 million (63.25%) and 28.46 million (58.20%) out of 961.5 and 48.83 million broiler and layer birds, respectively (1). The province is the base for major poultry companies in the country and therefore represents the ideal site to access key informants of different production systems.

The major chicken producing areas of central and north Punjab and a list of stakeholders to be interviewed were identified during informal discussion with poultry experts at the University of Veterinary and Animal Sciences Lahore and Poultry Research Institute in Rawalpindi, Pakistan. Target interviewees included federal and provincial poultry research officials, commercial chicken producing farmers, backyard farmers, poultry, and egg traders and owners of vertically integrated and processing companies (**Table 1**). They were selected such to have a broad representation from all parts of the chicken industry from production to distribution level. Each participant was contacted by the first author and briefed about the project. If they agreed to participate, interviews were conducted.

TABLE 1 | Type and number of participants interviewed.

Type of participant	Broiler production	Layer production
Federal and provincial poultry research officials	1	1
Focus group discussion with independent broiler farmers ($n = 9$)	1	0
Managing director of fully integrated company	1	0
Production managers of partially integrated companies	2	2
Independent chicken growers (environmentally controlled)	4	3
Independent chicken growers (semi-environmentally controlled)	0	2
Backyard farmers	0	2
Chicken and egg traders	3	2

Data Collection

Qualitative data were collected using an interview guide that included questions on production system types, sourcing inputs, output distributions and chicken disease management (**Supplementary Material 1**). At the same time, quantitative data on the proportions of market share and value chain flows were collected. The identities of all participants were anonymized to comply with ethical and business confidentiality requirements.

Scoping Interviews

Initially people with extensive experience and knowledge of the chicken (broiler and layer) industry and food systems were identified and approached for scoping interviews. The aim of these interviews was to gain a high-level overview of the chicken production, its structure, types, trading systems, and disease control systems. Additionally, these interviews were used to identify the major key informants (KI) and stakeholders involved in the chicken value chain, who could then be subsequently contacted for more detailed interviews.

During the scoping interviews, participants were asked to: (1) describe the different production systems in terms of purpose, species, management, husbandry (including housing), and number of birds; (2) estimate the proportions of different poultry production systems in Pakistan; (3) provide an overview of the value chain nodes in the chicken production systems including identification of stakeholders and key markets or infrastructures.

Key Informant Interviews and Focus Group Discussion

Following the scoping study, the KIs or stakeholders identified by the participants of the scoping interviews, were interviewed using semi-structured interviews (**Table 1**). A FGD ($n = 1$) with nine independent broiler farmers was initially conducted, but this approach was replaced by face-to-face interviews with key informants ($n = 23$), as the FGD was perceived to be inefficient and unproductive due to cultural dynamics.

During the FGD and KIIs respondents were asked to describe the following: (1) flock size and type of birds; (2) sources of inputs (feed, vaccination, veterinary services); (3) types and distribution of outputs (live chicken, meat, eggs, manure); (4) types of people involved (buyers, retailers, brokers, traders); (5) flows of inputs and outputs and their association with one another; (6) amount of different outputs obtained; and (7) institutions and people involved in disease reporting, control and management.

Interviewees were asked open-ended questions (e.g., "what are different ways of distributing outputs from chicken farming?"). Various prompts were used to explore and clarify details on activities, people involved and product flows. The participants were asked to describe and discuss people, inputs, outputs, flows, and quantities in the system. During this process, the interviewer drafted flow charts that participants could clarify and amend. This iterative process was followed to create a preliminary map of the system by the interviewer; it was subsequently checked and approved by the interviewee. All interviews were conducted in Urdu language by the principal author and were audio recorded. Additionally, summary notes were taken of all discussions held. The complete question guide is available in **Supplementary Material 2**.

Data Analysis

Through careful listening of the audio recordings the data were translated and transcribed. The notes and flow charts taken during the interviews and the FGD were then added to the transcribed recordings in a Microsoft Word document which allowed initial familiarization with data and preliminary structuring of information.

Analysis was done in two parts: first, a mapping analysis was performed to assist in the creation of flowchart diagrams, building on the drafts from the KIIs. This step allowed the creation of mapping profiles for different sections of the broiler and layer systems. These showed the type of people involved, flow of inputs, outputs and other chain characteristics that are key components of broiler and layer production systems. Where possible, proportions, or sizes were indicated as integers and with arrows of variable widths, according to the magnitude of the flows.

Secondly, thematic analysis was performed to identify meaningful themes that would provide understanding of the processes, governance, and interactions within the chains. Data were imported from Word into NVivo software (NVivoPro, version 11) and coded and arranged on the basis of similarity of information in the codes. Subsequently, the various themes were identified based upon codes that described an activity or characteristic of a value chain node. This thematic analysis was used to refine the mapping profile generated in the first step. Every time an interaction, stakeholder or activity was mentioned as associated to a particular chain, this was added to the mapping flow-chart diagram. Based on the broad topics asked during interviews, key themes of governance in the form of dominance, management, health provision, and identification of structural deficiencies in the poultry sector were identified and coded. All categories and themes were proof-read by co-authors as a quality check to avoid any gaps in theme identification and categorization.

RESULTS

Structural Components and Types of Chicken Farming

Respondents described that over 75–80% of chicken meat and egg production in Pakistan was commercial in environmentally controlled intensive systems, while backyard birds accounted for 20–25%. Keeping chickens in the backyard was described as subsistence to meet household meat and egg consumption using free range systems. Three production systems for broilers and two for layers were identified (**Table 2**). These systems include: Fully integrated production (only for broilers), partially integrated production, and independent farming (**Figures 2**, **6**). Fully integrated producers were those where one single company managed the value chain, from grandparent production to finished chicken products sold to retailers or consumers. Partially integrated producers included companies that managed parent stock/breeder, finishing of broilers or layers, with varying control of the distribution of products or finished birds (but no grandparent stock). Independent farmers were described as broiler and layer growers who practiced rearing of day-old chicks (DOCs) to the level of finished birds in the case of broilers, and to egg production in the case of layers.

Broiler Systems

Characteristics of Broiler Farming Systems

Commercial broiler farming management is divided into environmentally controlled and open-sided house systems. Major broiler producing areas in Pakistan were reported to be in Punjab, in particular in the districts of central and north Punjab (**Figure 1**).

Major production system with their value chains are shown in **Figure 2**. Participants estimated that 97–98% of broiler commercial farming in Pakistan is within environmentally controlled houses characterized by automatically controlled temperature, humidity, feeding and water supply. Housing capacity is around 30,000–40,000 birds per house, with an average live weight of 1.5–2.0 kg per bird at the end of production cycle and a feed conversion ratio (FCR) of 1.2–1.6. Open-sided house broiler systems were reported to be used in <2–3% of all broiler production. In these systems birds are kept in open-sided houses (2,000–5,000 birds per house) with no control over the temperature of the house and manual provision of feed and water. Open-sided house farming was perceived to be decreasing rapidly due to the "increased risk of disease outbreaks," "poor management of birds under extreme weather conditions," "increased mortality rate," "poor feed conversion ratio," and the "reduced number of finished birds" produced in this system.

Types of Broiler Birds

Key informants reported that Arbor acres, Hubbard, Cobb, and Ross are the broiler breeds most often used in Pakistan. It was perceived that Hubbard breed was more popular in the past, but has lately been replaced by Cobb accounting for 50% of total broiler production. Hubbard, Ross and Arbor acres were estimated to represent 25, 15, and 10%, respectively. This shift from Hubbard to Cobb was believed to be due to a change in farmers' and consumers' preferences. The major reasons included "better FCR," "comparable quality of meat," and "increased amount of breast meat per bird." Breast meat was reported to be directly related to profit gained, and hence preferred.

Mapping of the Fully Integrated Broiler Production Systems (FIBP)

These systems were characterized by single ownership of the entire value chain (**Figure 3**). There were two fully integrated companies in Pakistan each with 1.5–2 million broiler DOC capacity at any one time. Their contribution toward total broiler production in Pakistan was estimated at 10%. These companies were reported to import and breed broiler grandparents to produce broiler parent stock. These parent stock DOCs were supplied to commercial broiler breeders (20–30%), partially-integrated broiler companies (60–75%), and to their own parent

TABLE 2 | Main characteristics of broiler and layer production systems.

	Type of integration	Grandparent stock (GP)	Parent stock (PS)	Grower and production farms	Housing	Feed source	Veterinary services	Contracts	Value chain	Processing and packing	Market type	Export
Integrated broiler production	Fully integrated broiler production (FIBP)	Owned	Owned	Owned broiler grower farms	Environmentally controlled	Owned	Privately hired	No actors at this point	Owned	Owned	Processed market	Processed meat
	Partially integrated broiler production (PIBP)	No actors at this point	Owned	Owned and contractual broiler grower farms	Environmentally controlled	Owned	Privately hired	With IBP and middlemen	Owned and middlemen moderated	Owned	Processed and wet market	Live birds and processed meat
Independent broiler production (IBP)		No actors at this point	No actors at this point	Owned broiler grower farms	Environmentally controlled and open-sided house	Owned and commercial feed	Privately hired and public services	No actors at this point	Middlemen moderated	No actors at this point	Wet market	Live birds
Integrated layer production	Partially integrated layer production (PILP)	No actors at this point	Owned	Owned layer grower farms	Environmentally controlled	Owned	Privately hired	Yearly contracts with target customers	Owned and middlemen moderated	Owned	Processed and wet market	Eggs and spent hens
Independent layer production (ILP)		No actors at this point	No actors at this point	Owned layer grower farms	Environmentally controlled, semi-environmentally controlled and open-sided house	Owned and commercial feed	Privately hired and public services	Yearly contracts with target customers	Middlemen moderated	No actors at this point	Wet market, retail outlets	Spent hens
Backyard farming (BF)		No actors at this point	No actors at this point	Rear birds in backyards	Free range	Mainly scavenging	Public services	No actors at this point	Middlemen moderated and direct sale	No actors at this point	Wet market	No actors at this point

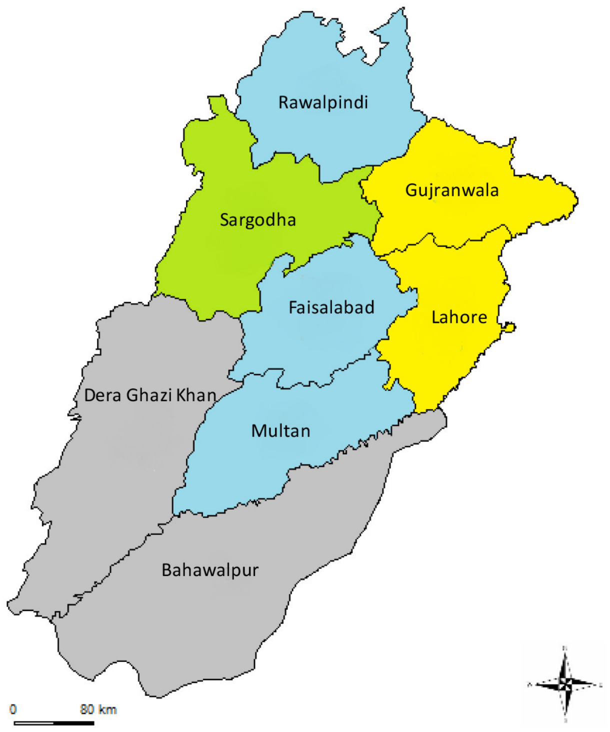

FIGURE 1 | Major (colored) and minor (gray) commercial chicken producing areas of Punjab, Pakistan. Yellow: major broiler producing areas, green: major layer producing areas, blue: both broiler and layer producing areas. Map has been downloaded from https://gadm.org/maps/PAK/punjab_2.html and modified according to our data.

breeder farms (5–10%). The latter produced commercial broiler DOCs supplied to their own farms (10–15%) and to independent broiler farmers (85–90%). Interviewees explained that these companies owned feed mills used to provide feed not only to their own farms (breeder and broiler grower farms) but also to sell commercially. This was reported to be one of the most profitable commodities in integrated chicken production.

Central management of these companies' broiler growers was reported to ensure good farm practices and quality of the finished product, through maintaining environmentally controlled systems and strict biosecurity protocols. Company-operated vehicles were said to transport finished birds from their grower farms to processing plants that are mainly located on the outskirts of Lahore city, with the capacity to process a maximum of 50,000–60,000 birds per day. It was also reported that these companies are Halal (ISO 9001) and international food safety management system (ISO 22000) certified and operate using a hazard analysis critical control point system. Chickens were processed into frozen carcasses, meat cuts and ready to cook products (98–99%), with 1–2% by-products that included shanks with claws, feathers, intestines and blood. Shanks with claws were exported to China while other by-products were sold to commercial rendering plants. Finished products were supplied to the company's own outlets and to independent retail grocery shops, supermarkets, restaurant chains, and various institutions like hotels and clubs throughout Pakistan via company-operated refrigerated vehicles.

Interviewees explained that the processed products were mostly used domestically in the country, although frozen carcasses and ready-to-cook products were also exported to Middle Eastern countries like Qatar, Abu Dhabi and Bahrain. Export was described to be the only part of the FIBP value chain moderated by middlemen. In case of high demand of processed chicken from target customers, these companies were reported to purchase broiler birds from independent broiler farmers. Such deals were described to be devoid of any middlemen involvement and required strict bird health criteria to complete the purchase, which include birds being negative for Salmonella, Mycoplasma infection, and free from antibiotic residues.

Partially-Integrated Broiler Production Systems (PIBP)

Operations of PIBP are shown in **Figure 4**. Respondents revealed that the market share of PIBP was 16–20% of the total broiler production in Pakistan. PIBP starts operation at the level of parent stock (breeder) farming. A minority of these companies were found to practice broiler parent stock farming but do not have their own distribution chains and processing plants, while the majority purchase the broiler parent stock DOCs from the FIBP. All of the PIBP were described to have their own broiler parent stock farms, own broiler grower farms, and own feed mills. The DOCs produced were sold to either company-owned broiler grower farms, independent farms or contractual farms. Contractual farms are those with long-term supply contracts; they are bound to buy broiler DOCs and feed from PIBP in return for animal health services and purchase of the finished birds. All housing was environmentally controlled with an average of 30,000–40,000 broiler birds per house and 4–5 broiler houses per farm.

The PIBP broiler value chain was found to include either informal middleman-governed distribution chains, or formal company-operated distribution chains. The respondents explained that the majority of finished broilers (80%) were sold as live birds to designated brokers who have contracts with the companies. These brokers have additional contracts with traders to collect finished birds from the farms and supply them to live bird markets ("Mandi" in local language Urdu; a wholesale live bird market where birds are sold by open auction) or independent poultry processing plants. The remaining 20% of the finished broilers produced were said to undergo processing to finished broiler products via company-operated processing plants followed by transport via company-designated refrigerated vehicles to local restaurants, grocery outlets, supermarkets, and the companies' own outlets in the country.

The PIBP as explained by the interviewees were in transition from independent broiler farms toward a fully integrated system. The reasons reported for this transition were the "unstable live broiler market," "price fluctuations due to seasons and festivals," and to "bypass middlemen" dependency in the distribution chains.

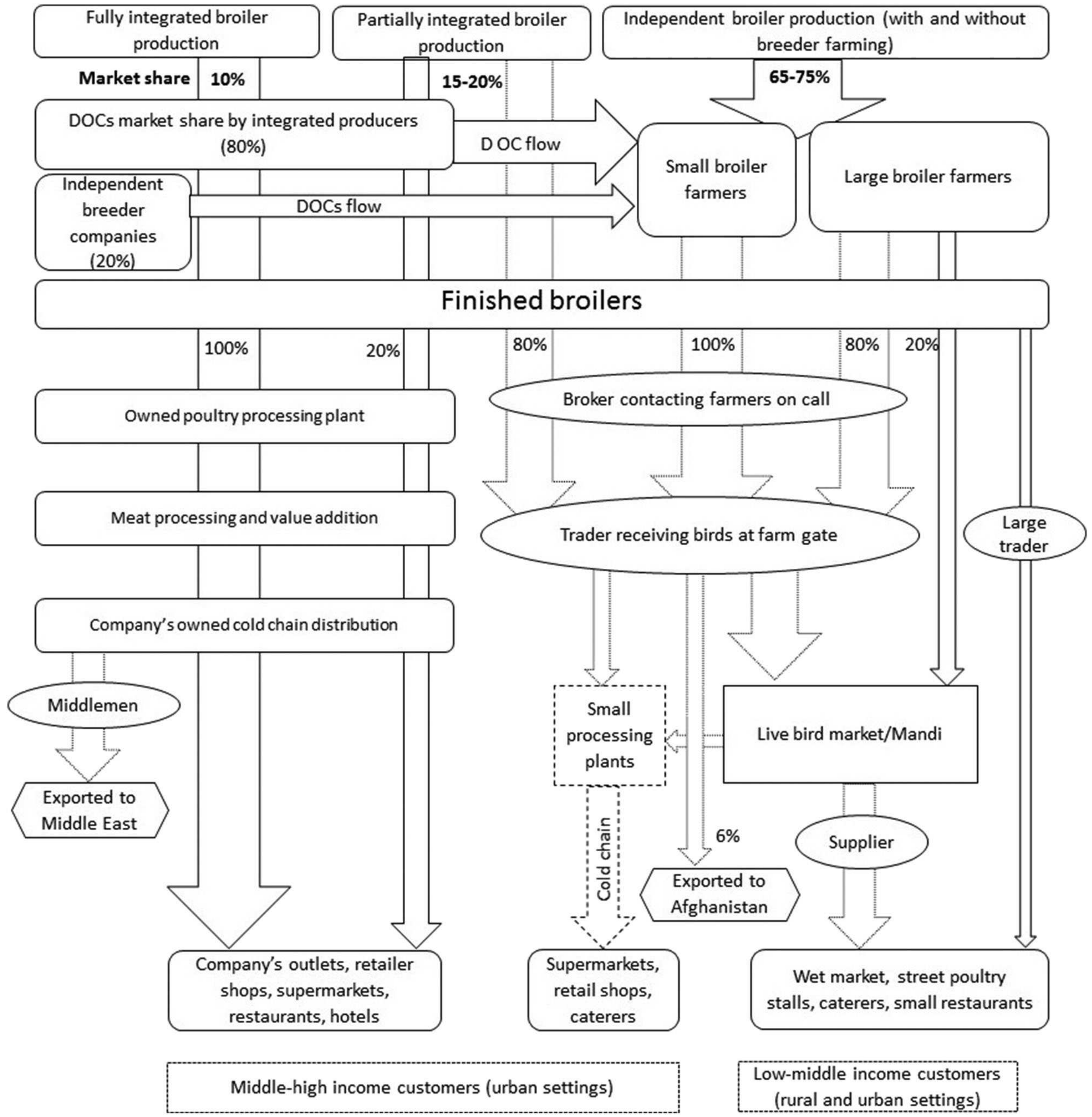

FIGURE 2 | Broiler production systems in Pakistan, their market shares and associated value chains. DOC indicates day old chicks, Mandi in local language Urdu is a wholesale live bird market where birds are sold by open auction. Dotted lines show the parts of chains operated by the middlemen. Numbers in and around arrows and width of arrows indicate the market shares.

Independent Broiler Production (IBP)

It was estimated that independent broiler farming (**Figure 5**) is a major contributor (65–75%) to the number of finished broilers produced in the country. The farmers in IBP were only involved in the raising of broiler DOCs to the level of finished broiler. Most of the major inputs such as feed and DOCs were said to be purchased directly either from fully or partially integrated companies, or from independent feed mills and hatcheries. Finished broilers were sold to the brokers at the farm gate as live birds. Output distribution chains in IBF were mainly regulated and controlled by middlemen including brokers, traders, suppliers, and retailers.

Farm level decisions in IBP such as selecting breed of broilers, sourcing feed, and vaccination were reported to be made by either the farmer, farm manager or farm

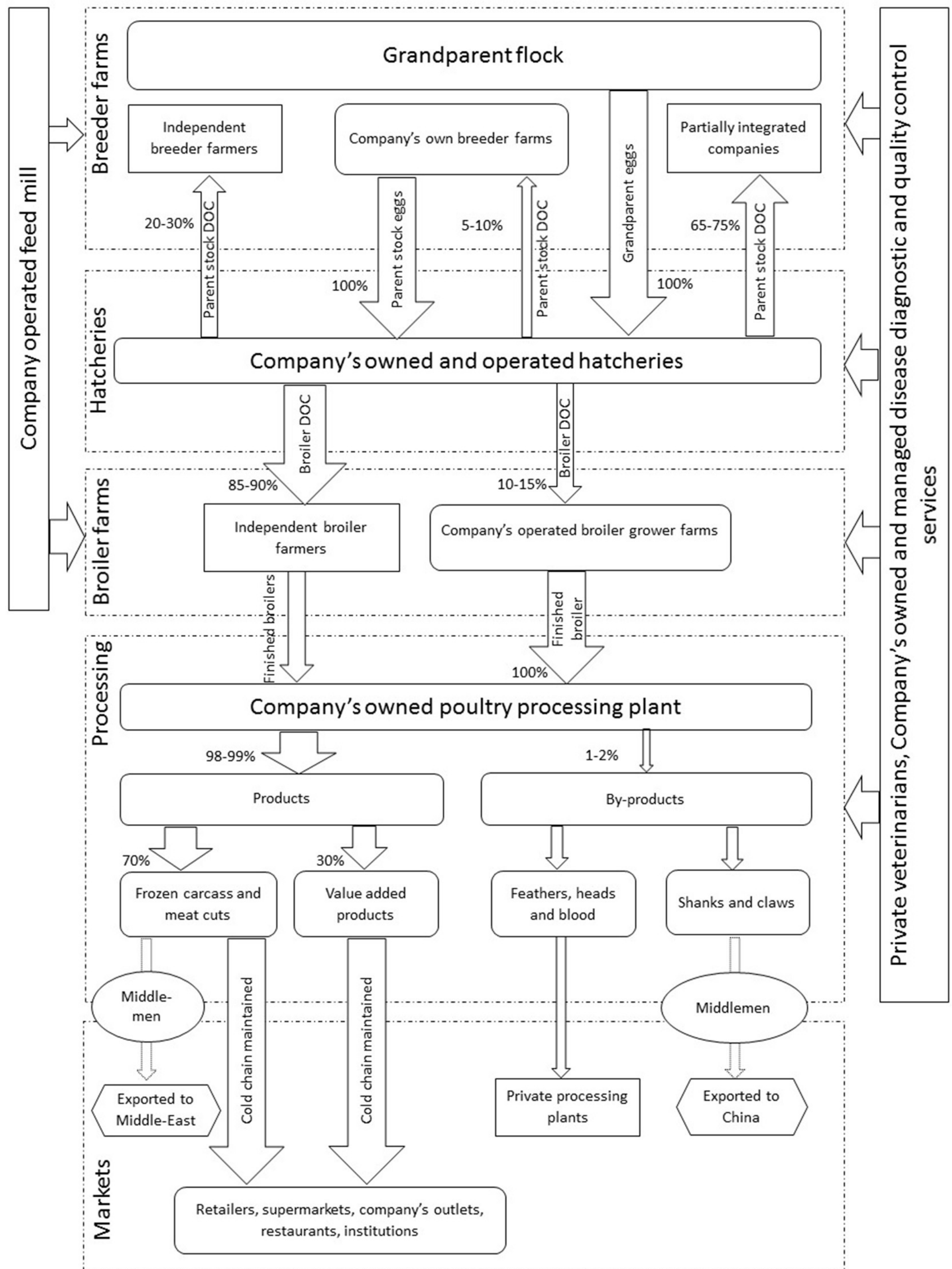

FIGURE 3 | Map of the fully integrated broiler production system with distribution chains and target markets. DOC indicates day old chicks, numbers in and around arrows and width of arrows indicate the market share. Dotted lines show the parts of chains operated by the middlemen.

supervisor. These decisions were reported to be autonomously made without being influenced by any FIBP or PIBP, despite them being major providers of DOCs and feed to independent farmers.

Types of independent broiler farming

Independent broiler production was further categorized into large and small scale depending on total housing capacity. Small scale broiler farmers were described to have capacity

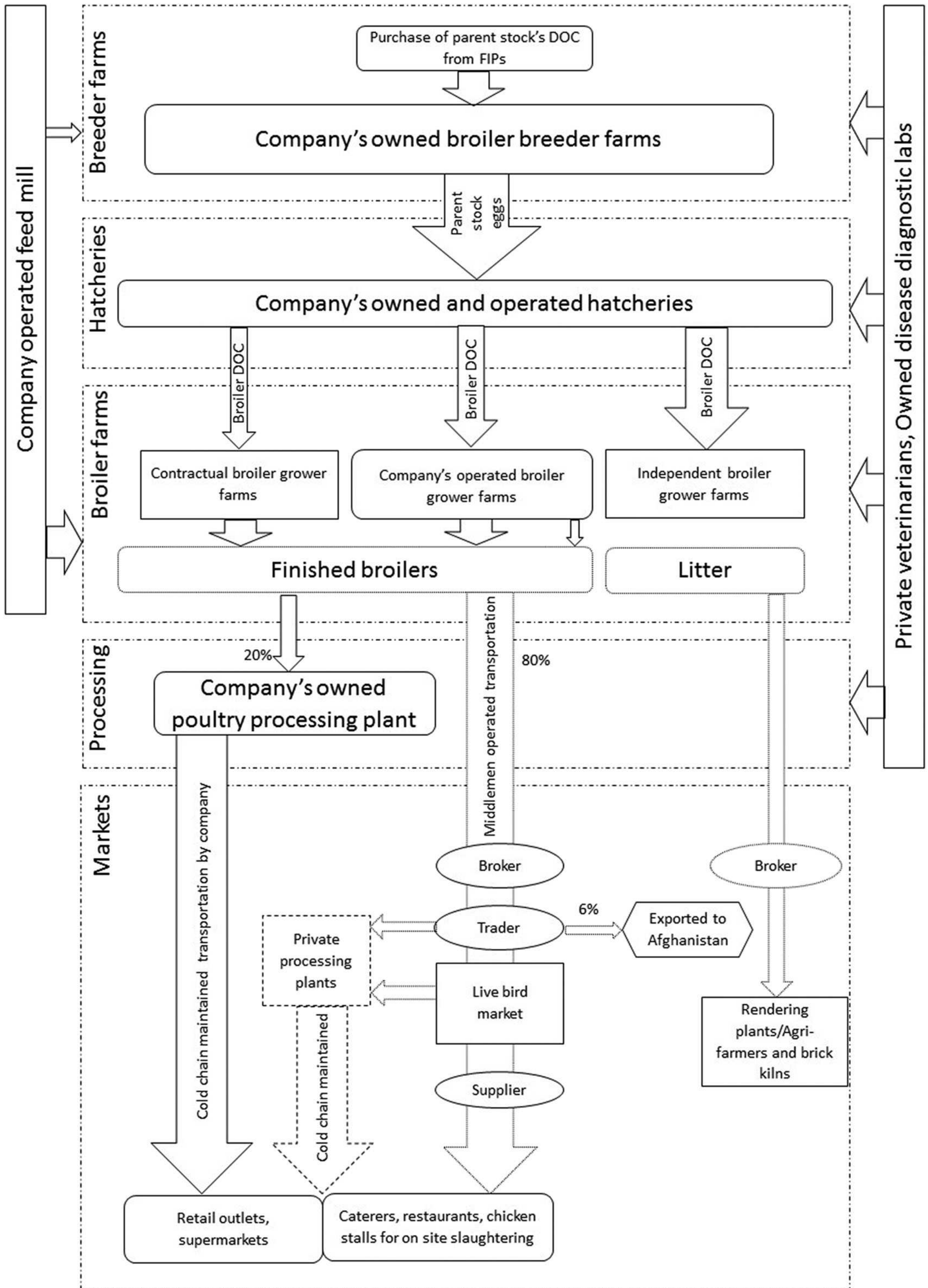

FIGURE 4 | Map of partially-integrated broiler production system with distribution chains and target markets. DOC indicates day old chicks, numbers in and around arrows and width of arrows indicates the market shares. Dotted lines show the parts of chains operated by the middlemen. FIPs refers to fully integrated production system.

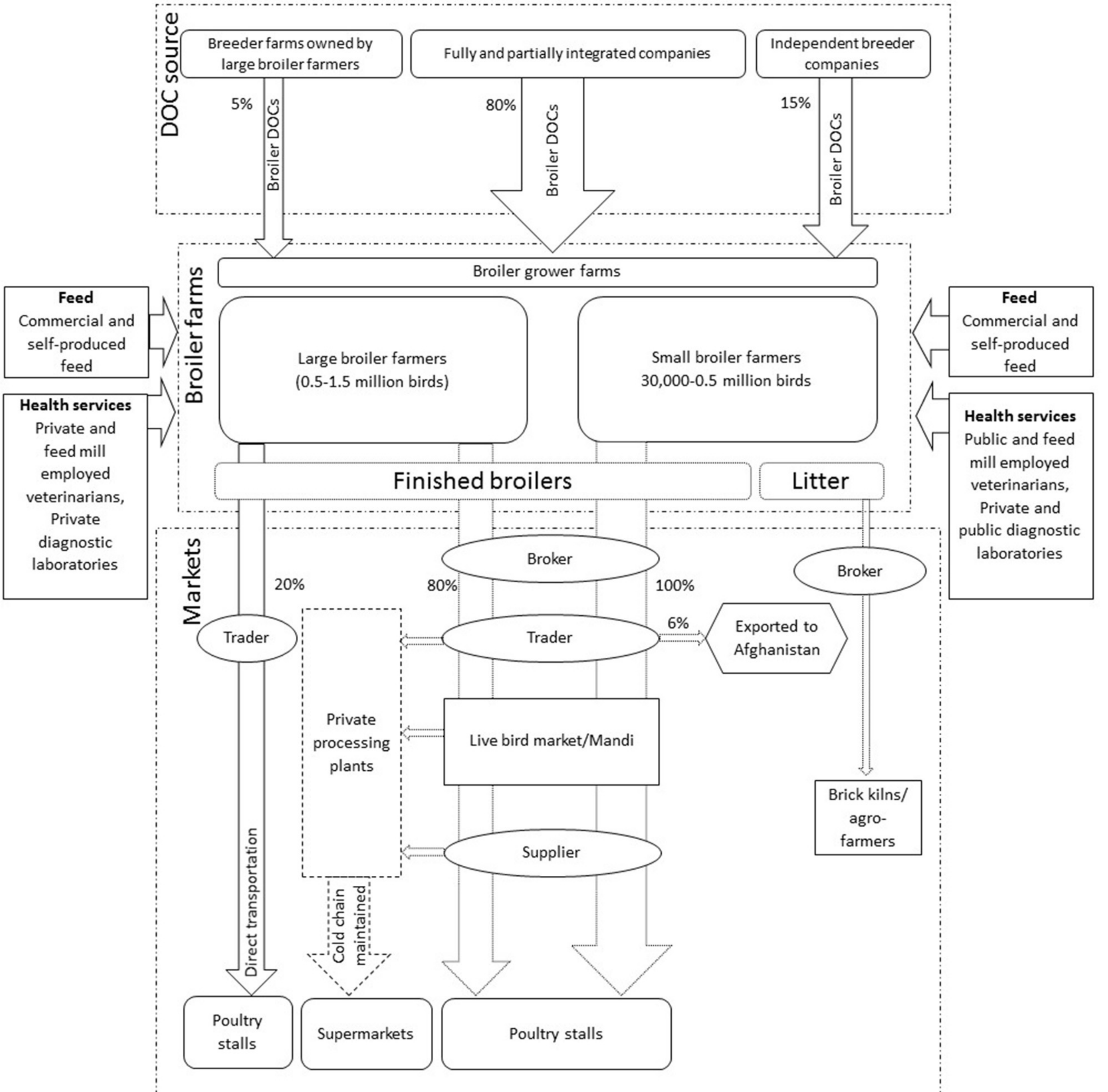

FIGURE 5 | Map of independent broiler farming, its types, distribution chains, and target markets. DOC indicates day old chicks, Mandi in local language Urdu is a wholesale live bird market where birds are sold by open auction. Dotted lines show the parts of chains operated by the middlemen. Numbers in and around arrows and width of arrows indicate the market shares.

to house between 30,000 and 0.5 million broiler DOCs, while large scale broiler farmers could house between 0.5 and 1.5 million birds; very few farmers were reported to have capacity for >1.5 million broiler birds. To reduce the cost of production and increase efficiency, it was reported that 85–90% of IBP is within environmentally controlled systems. The major input costs as perceived by the farmers were for feed (60–65%) and DOCs (25–35%), followed by vaccination and medicine (12–15%). Feed and DOCs were provided directly to the farm level by the independent feed millers and breeders, FIBP, PIBP via company-operated vehicles without the involvement of any middlemen. Large scale broiler farmers tended to produce their own feed with extra feed purchased commercially if needed. In contrast, small scale broiler farmers were reported to depend on commercially available feed, mostly supplied on a credit basis. The majority of DOCs (80%) supplied to these independent farmers is provided by 10–12 companies (FIBP or PIBP), and their distribution offices were reported to be located around the

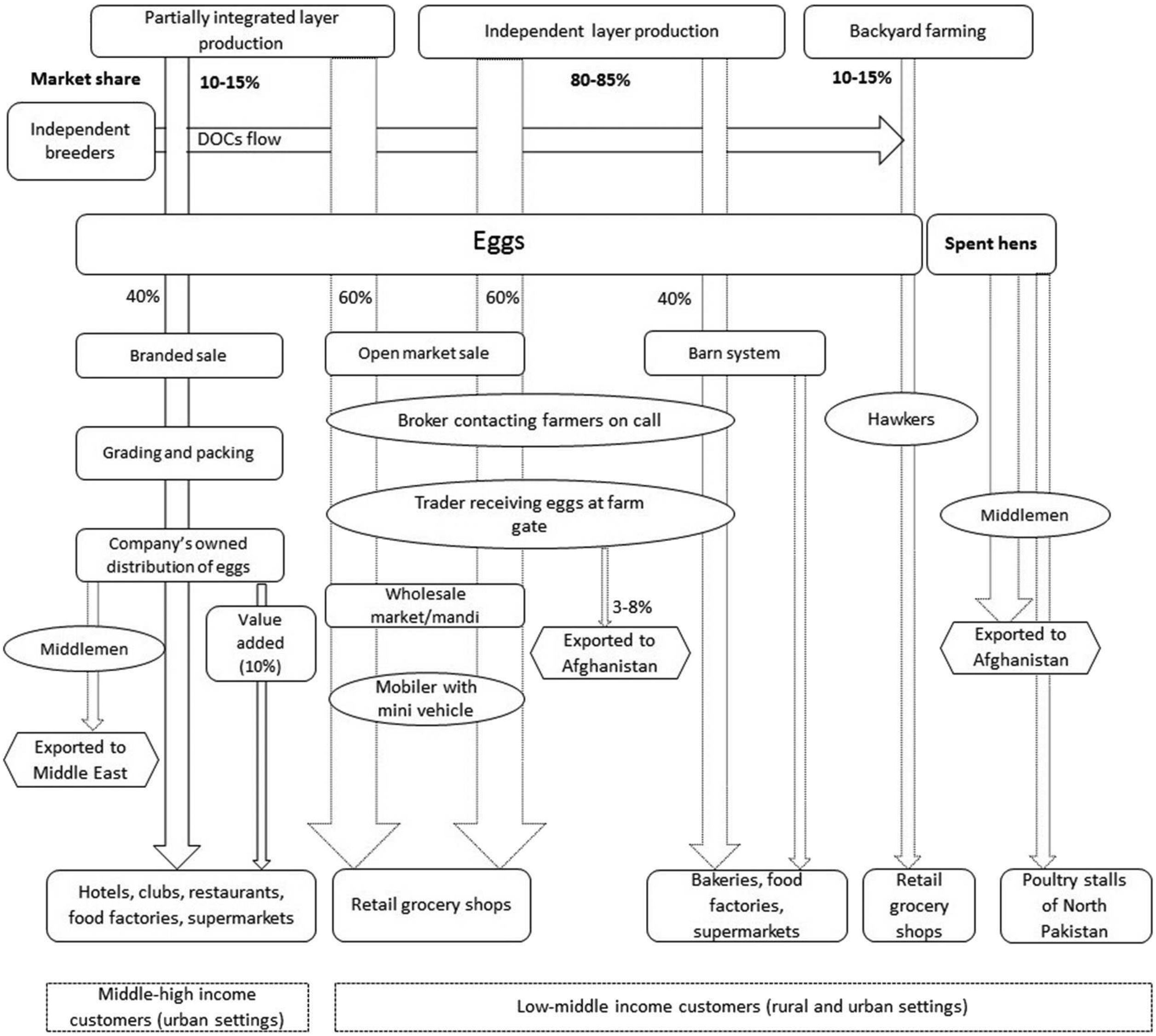

FIGURE 6 | Layer production systems in Pakistan, their market share and associated value chains. DOC indicates day old chicks, Mandi refers to the wholesale market for eggs. Dotted arrows show the chains operated by the middlemen, numbers in and around arrows, and width of the arrows indicate the market shares.

major poultry producing areas, such as central and north Punjab. These companies have 80% of the country's parent stock flocks, while the remaining 20% parent stock is distributed among small and large independent broiler breeder companies.

Distribution and value chains in IBP

Numerous chains with middlemen, live bird market and wholesale markets were found for the sale of finished broiler within IBP (**Figures 2**, **5**). These distribution chains were dominated by three types of middlemen, namely brokers, traders, and suppliers. A broker was defined by the respondents as an agent that deals with farmers and traders in order to purchase finished broilers. They were found to be actively communicating with the local farmers and traders to negotiate deals regarding the farm gate price of finished broilers. A trader was defined by informants as a person that purchases birds on credit from a broker, gets commission, and transports birds from farms to poultry wholesale markets. Informants explained that the sales of birds at the level of farmer and broker were cash based, whereas sales between broker and trader were mostly credit based. Suppliers ("gari wala" in Urdu means a person with a vehicle to transport birds) were responsible for transporting birds from live bird markets to the poultry stalls but in less capacity compared with traders; these purchases were in cash. Poultry stalls or shops are the commercial premises where live birds are kept and halal-slaughtered per demand. In northern Punjab, including districts of Chakwal and Rawalpindi, some large-scale farmers were reported to practice direct transportation of finished broiler to the Mandi to bypass brokers and traders, but such farmers also depend on open auctions conducted by traders in live bird markets to sell their products.

Broiler Chicken Marketing Profiles

Independent broiler farming (IBF) was described as a major contributor to Pakistan's broiler production. Live bird markets serving this production system dominate; they link brokers, traders and suppliers in the sale of finished birds (**Figure 5**). Farmers expressed distrust toward these middlemen for creating price fluctuations of finished birds and eggs at farm gate and market level. The live bird markets were described as wholesale markets where live birds from various sources were aggregated via middlemen and further distributed to retail outlets. These markets were described to be mostly operational in big cities, like Tollinton and Sheranwali market in Lahore, or in high chicken producing districts of the country. These markets also supply chicken to independent poultry processing units situated around big cities. In small cities, brokers and traders purchase birds directly from the farm and supply them to retailers (i.e., chicken stalls/butcheries).

To ensure halal slaughtering and respond to consumer preference for freshly slaughtered meat at cheaper rates, wet chicken markets in the form of retail outlets (chicken stalls) were described to be more common than other sources. These stalls were distributed all over the country in and around residential areas, serving freshly slaughtered halal meat daily based on demand. They were reported as the major provider of chicken meat to low- and middle income customers. Conversely, the FIBP and PIBP supplying a wide range of value-added products tend to target high-income consumers by selling these processed products at a higher price in more formal settings and ensuring that food safety standards are met.

Commercial Layer Farming

Figure 6 shows the major layer production systems in Pakistan. Respondents described layer farming as a growing sector in Pakistan, transforming rapidly from conventional to modern farming practices in order to cater to the increased demand for eggs and egg-based food products. It was reported that 60–70% of the layer farming was environmentally controlled (as described in section Characteristics of Broiler Farming Systems) while the remaining 30–40% were open-sided housing systems. Layer farming was perceived to be in transition from the conventional open-sided house with floor rearing system to modern environmentally controlled cage systems. Informants respondents said that almost 80 million layer birds were reared in cages, almost 20 million in locally produced cages and 117 million on floors in open-sided houses.

Respondents stated that layer production is less profitable than the broiler production due to; a longer production cycle creating seasonal placements (February–March) of layer DOCs in rearing houses, high feed costs, and a lower probability (33%) of getting female chicks out of hatched eggs. A total of 40,000–50,000 layer breeders were present in Pakistan; they were distributed among 7–8 layer breeder companies and big layer production farms. Layer farming was mostly practiced as independent farming or as partially integrated layer production. Processing of table eggs was not reported to be commonly practiced and only one independent company throughout the analysis was reported to process eggs into egg powder and packed liquid eggs.

Types of Layer Birds

The major layer breeds in Pakistan were Hy-Line (W-98, W-36, CV-22), Babcock, Lohman (LsL light, LsL classic), Novogen (white light, brown light), H&N international (nickchick, crystal nick, coral brown) and Hendrix genetics (Shaver, Bovan and Hisex). LsL light was believed to be the most popular breed in Pakistan due to "high egg production efficiency" and its "fitness for the cage system" because of its light weight. Average peak production of commercial layers in Pakistan was described to be reached at the age of 26–29th weeks with an average number of 320 eggs produced per bird per unit production cycle. Major layer producing areas reported in Pakistan included districts of central Punjab (Kamalia, Arifwala, Okara, Sammundri, Sargodha, and Faisalabad), north Punjab (Chakwal and Rawalpindi) and south of Sindh province (Karachi and Hyderabad) (**Figure 1**).

Partially Integrated Layer Production System (PILP)

The interviews revealed that no fully integrated layer production system exists in Pakistan (**Figure 6**); there were no reports of production and breeding of layers' grandparents in the country. The layer parent stock is imported from United States and Europe, and kept either by partially integrated companies or by independent breeders. Companies were designated as partially integrated due to their absence of keeping layer grandparent and partial ownership of distribution chains (40%). All major inputs like feed and DOCs were reported to be provided by company-owned feed mills and hatcheries.

The market share of egg production of PILP in Pakistan was estimated to be around 10–15% (**Figure 6**). Only two layer companies were reported to be partially-integrated with environmentally controlled cage systems (**Table 2**) for layer rearing and production; owning their feed mills, and diagnostic laboratories. Both were involved in grading and packing of eggs and company-operated distribution of the eggs to the target customers.

The partially-integrated layer companies had their own egg distribution chains, called "branded sale" (40%), while the rest of supply was moderated by middlemen (60%). Branded sale was reported to include grading and packing eggs before distributing it to hotels, clubs, restaurants, supermarkets, retail shops, and company owned outlets via company-operated vehicles. Moreover, such companies were also reported to add value to eggs by Omega 3 enrichment and deeply-pigmented yolk in line with consumer preferences. These value-added eggs were only 10% of all eggs produced by partially integrated companies.

Independent Layer Production (ILP)

The market share of ILP was about 80–85% of the total egg production in Pakistan (**Figure 6**). Only a few farmers kept layer breeders in ILP and the majority purchased DOCs either from independent breeders or PILP. Farmers may or may not have their own feed mills in case of ILP. It was reported that 70% of the ILP was environmentally controlled farming (as described in the section Characteristics of Broiler Farming Systems) while 20% was semi-environmentally controlled where temperature and humidity were controlled only in summer with minimum ventilation in winter by manually regulating the house vents. The share of open-sided house farming was reported to have reduced from 40 to 8–10% in the last decade. This reduction was believed to be due to increased competition for better quality eggs, and increased consumer demand of eggs. The interviewees predicted that the remaining open-sided house layer farms will be completely replaced by semi or completely environmentally controlled farming in the coming years.

In open-sided house based farming layer birds were kept on the floor during the production phase with manual egg collection performed 4–5 times a day, in contrast to cage production where all eggs were automatically collected once a day, thereby reducing labor costs. In ILP, 60% of the eggs were reported to be traded through open markets dominated by brokers, traders and "mobilers" (**Figure 6**). Mobilers were described as traders who distribute eggs to the retail outlets via motorcycle or mini vans, similar to suppliers in broiler distribution. Moreover, 40% of eggs were traded through the so-called "barn system" in which a yearly contract of egg supply was either signed with big traders, bakeries or food production companies. Spent hens in PILP and ILP were reported to be exported as live birds to Afghanistan or sold to northern hilly areas of Pakistan via traders.

Backyard/Chicken Production

Backyard production in Pakistan was defined as keeping 2–3 birds in the backyard of a house for recreation or domestic use. Backyard production was predominantly found in remote areas of Pakistan where it is difficult to maintain a continuous supply of inputs. The backyard birds were reported to be mostly kept in rural areas to meet household needs of eggs and meat with surplus eggs and spent birds sold to hawkers. Hawkers were said to sell these birds to local markets/retailers and wholesale markets of big cities like Lahore. The breeds that were kept for backyard farming included Desi, Fayoumi, Rhode Island Red, Naked neck, and their crosses. The housing system was free range and feed sources included scavenging and kitchen by-products. Major areas of backyard farming included rural areas of Chakwal, Mianwali, Bhakkar, and Dera Ghazi Khan Districts of Punjab. As the backyard farming was scattered through secluded rural areas of Pakistan, backyard farmers were reported to have only access to health facilities provided by rural government veterinary or para-veterinary staff.

Dynamics of Chicken Markets

Interprovincial unregulated transport of chicken was evident in the study. The production surplus in Punjab province, along with high production prices in other provinces were described as major factors that caused movements of birds from Punjab to other provinces. Some participants explained that traders from other provinces acquired birds from Punjab if there was enough profit margin left after deducting transportation cost and weight loss during transport. The price difference of broiler meat between Punjab and other provinces was estimated at 40 PKR/Kg (0.26 USD/Kg) live weight and farmers reported that traders from other provinces traveled a distance of 900–1000 Km toward central Punjab to purchase live birds at a cheaper rate.

Respondents described cross-border trade with Afghanistan for exporting finished broilers, spent hens and table eggs from Pakistan. Due to a lack of import standards in Afghanistan these exports were described to be free of any safety checks and quarantine procedures. This trade was reported to be moderated by the traders on either side of the border based on credit or cash depending on the type of agreement. However, the respondents showed concerns about "cash recovery" in this trade.

Commercial broiler and layer producers were located close to urban settlements to allow easy access to the markets. A rapid increase in using processed meat and ready-to-cook chicken products by consumers was reported. This was mainly due to increased number of large- and small-scale slaughterhouses around the major poultry producing areas of Punjab province. Improved meat processing technologies, good hygienic practices, and strong marketing tactics, with electronic and print media used to increase consumer awareness about the safety and hygienic food, were the major reasons reported for increased consumption of chicken products. Such marketing campaigns were moderated by meat and egg processors mostly targeted at medium-high income customers as low-income groups cannot afford to pay 50–100 PKR (0.5–1 USD) extra for the same weight of chicken that they could easily get from informal chicken stalls. The situation was described to be similar for egg marketing. Respondents also hypothesized that with increasing demand of ready-to-eat products and ease in household handling of processed meat these markets could overtake wet markets in the future.

Health Services Providers and Structural Deficiencies Identified in Chicken Sub-sector

The availability of poultry health services varied among different chicken production systems. Two main types of stakeholders (**Table 3**) were reported to provide health services to farmers, namely those in the government (70%) and private (30%) sectors. The government sector was found to be actively involved in passive surveillance of diseases like AI, providing some vaccines and capacity building against chicken diseases while the private sector was involved in providing vaccines and diagnostic services. "Trust in quality," "price of available services," and "easy access to the health services" were stated as a major factors in selecting available diagnostic services (government/private laboratories) and control measures (local/imported vaccines). Backyard farmers and small-scale independent farmers relied on government veterinarians, feed, and medicine company veterinarians, experienced para-veterinary staff as well as government and small private laboratories for obtaining bird health services. Vaccines used in these systems were mostly locally produced. Commercial chicken farmers in FIBP, PIBP, PILP and large-scale independent farmers tended to hire their own private veterinarians along with visiting experienced private consultants and used well-established private and government laboratories in big cities for disease diagnosis.

This is because of their large farming setups and desire to ensure good quality finished products through regular monitoring of bird health. Some FIBP and PIBP reported having their own diagnostic laboratories for disease diagnosis, including for AI, which also provided commercial services to independent farmers. The integrated producers also reported a lack of interest in the government provided health and diagnostic facilities and vaccines, having concerns regarding quality of available services. The vaccines for AI and other poultry diseases mainly used by these farmers were either privately produced locally or imported from Europe and China. In general, layer and broiler farmers thought that vaccines were necessary to prevent and control infectious diseases like H9N2 AI.

Medicines and vaccines were reported to be purchased directly from regional distributors or veterinary pharmacies, and veterinarians were found to be involved in their marketing and sale. These veterinarians also provided free health consultancies to independent chicken farmers. Only one company (PIBP) was found to operate their own pharmaceutical units producing medicine including antibiotics for their own farming business and for commercial sale. In case of any notifiable disease outbreak, especially high pathogenic AI at the district level, it was the responsibility of the local government veterinary officer to inform the assistant disease investigation officer, who further informed the divisional disease investigation and control officer followed by provincial and federal reference laboratories. The Pakistan Poultry Association was found to be the major organization actively working as a link between government and poultry industry to address the issues of the poultry farming community at federal level. At provincial and federal level, strategies were developed and updated in consensus with Pakistan Poultry Association under the umbrella of Poultry Production Act, 2016, to devise and disseminate information on disease control and interventions. This included restriction of animal movement, adoption of strict control measures and increased surveillance in the affected areas. However, for low pathogenic AI H9N2 virus no special reporting system was stated during the interviews. In FIBP, PIBP and independent large-scale farming, internal disease reporting systems, including H9N2 AI infection, were reported that did not involve government veterinarians. Most of the reported H9N2 AI outbreaks in Pakistan happened between the months of March–April and October–November. The farmers were aware of such seasonal outbreaks and "mentally prepared" for losses during H9N2 outbreak months.

Respondents in all integrated and large-scale independent chicken production systems described burying or burning diseased and dead birds. Most of the small-scale independent farmers reported disposing of birds on landfills and in canals located close to their farms. The large-scale farmers showed concerns that such improper disposal and lack of regulations from government on disposal practices were major reasons for repeated outbreaks of H9N2 AI. Structural deficiencies as reported by the respondents during interviews are presented in **Table 3**.

DISCUSSION

The aims of this study were to characterize and map chicken production systems, associated value chains and to explore the options for chicken disease control in Pakistan. To the authors' knowledge, this is the first study to provide a detailed characterization of the chicken production systems and their value chains in Pakistan.

The mapping of the chicken production industry identified important differences in production types, chain structures, and marketing of finished products. The chain structure varied in terms of length and intricacy across profiles. Short chains were present in FIBP and some PIBP setups, while long chains were mainly found in independent production systems, where middlemen like brokers, traders, suppliers and mobilers were not only involved in distribution of products, but also in price control. While price control may be beneficial for single actors or a group of actors, it increases transaction costs and contributes to inefficiency within poultry value chains; this is in line with similar findings in other low and middle income countries (18–20). It was found that independent farming for broilers and layers was completely dependent on brokers and traders for selling finished chicken meat and eggs. Further down the distribution chain these middlemen relied on being able to sell live birds and eggs to wholesaler markets; a pattern also reported for Bangladesh (21). Control by middlemen was predominant in wet markets where price setting was used as a mechanism to influence supply and demand of chicken and its products. These findings are in accordance with studies in India (22) which associated high prices and inaccuracies in supply and demand with the presence of middlemen in poultry value chains. Despite the increase in transaction costs and middleman monopolization in the supply and demand of chicken and its products, the majority of farmers preferred to sell to brokers and traders at the farm gate because this cash-based sale was most convenient for them. This was the dominant type of transaction for partially-integrated and independent farming. It was similar to other studies conducted in Africa where farmers engage themselves in selling finished products at farm gate level to access cash quickly and to avoid transportation costs (23, 24). In these situations, ethics and attitudes of middlemen have the potential to influence the price of the finished product disproportionately (21). Complex distribution chains, with numerous middlemen, are known to limit profits to farmers (22, 25). For this reason, some farmers in north Punjab bypass middlemen by transporting and selling finished birds directly to the markets. Integrated companies on the other hand, for both layers and broilers, were involved in managing the whole value chain from the level of breeding stock to the distribution of finished products to ensure good quality of product and to reduce transaction costs. However, they have higher production costs due to applying strict hygienic measures for processing, value addition, managing transportation and advertisement costs. This results in a higher price of finished products (21), but they have better access to export markets and high end consumers.

People's perceptions about meat obtained from chicken stalls as fresh, halal, easy to access and cheap are factors causing wet

TABLE 3 | Major themes identified regarding management and health services by production system.

Themes	Sub-themes	Full integration	Partial integration	Independent production
Sector level management	Dominance	Day old chicks supply, Feed supply, Processed market	Day old chicks supply, Feed supply, Processed market	Wet market, Over all chicken meat and egg supply, Middlemen
	Price fluctuations	Slightly concerned, Economic instability	Moderately concerned, Economic instability	Highly concerned, Economic instability, Middlemen monopolization
	Role of poultry association	Farmer meetings, Disease control strategies	Farmer meetings, Disease control strategies	Farmer meetings, Disease control strategies
	Role of government	Poultry Production Act, 2016	Poultry Production Act, 2016	Price management Poultry Production Act, 2016
	Inter-farm distance	Highly concerned	Highly concerned	Moderately-highly concerned
Farm level management	Biosecurity	Strict biosecurity	Strict biosecurity	Variable biosecurity
	Labor staff	Technical and experienced	Technical and experienced	Non-technical and experienced, Technical and experienced
	Dead bird disposal	Burying, Burning	Burying, Burning	Burying, Burning, Throwing on landfills and water bodies
Animal health	Private services	Veterinarians, Vaccines, Diagnostics, Medicine supply	Veterinarians, Vaccines, Diagnostics, Medicine supply	Veterinarians, Consultant veterinarians, Vaccines, Diagnostics, Medicine supply
	Government services	No role	No role	Veterinarians, Vaccines, Diagnostics, Passive surveillance

markets to dominate. These findings are consistent with those of Karthikeyan and Nedunchezhian (26) in India who reported cheap prices of freshly dressed meat and accessibility of corner chicken/retail shops as major factors for preferring wet markets. Despite the high retail cost of processed products, a shift was perceived in consumer preference away from freshly slaughtered birds toward processed meat due to increased awareness about safe, hygienic, and value-added meat and eggs in Pakistan; as also reported in neighboring countries (26). This consumer shift could encourage integrated farmers to scale up processing operations and expand their business creating new potential for processed markets. However, similar to Bangladesh, Pakistani processed markets are not as popular as wet markets, as they do not have on-site and on-demand slaughtering (21). Moreover, the increase in the trend of processed meat consumption and the development of small and large private poultry processing units for catering has aided in the growth of domestic demand, and export of processed chicken products. Therefore, it makes financial sense to increase chicken production and processing in Pakistan as it could serve as a source of foreign exchange (27).

The chicken market in Pakistan (broilers and spent hens) is predominantly regarded as a live bird market and large independent and partially-integrated farmers were found to be involved in the export of live birds to Afghanistan–as previously reported (13). Farmers reported a lack of import standards for exporting live birds to Afghanistan and hence stated these exports as free from health and safety checks. However, such findings are not in accordance with Afghanistan poultry industry and import requirements (28) which details the criteria for importing chickens into Afghanistan.

Integrated companies in Pakistan were found to be involved in the export of processed and packed chicken meat and egg products including frozen carcasses, ready to cook items and value added meat and eggs; a practice reported earlier in India (26). However, these exports are minimal when compared with the vibrant domestic fresh meat and egg market. In 2012, total national production and consumption were approximately balanced at roughly 590 kilotons (13).

DOCs and feed in Pakistan are mainly supplied by integrated production systems, which is in accordance with findings from Kenya and Pakistan where dominance of large companies in supplying DOCs has been described (13, 18, 23). However, several small and large independent breeder farmers and feed mills, working in parallel with integrated companies have created a competitive market for DOCs and chicken feed across the production systems. Independent farmers in Pakistan were reported to be autonomous in making farm-level decisions about sourcing of DOCs, feed, vaccines, and selling finished birds and eggs without being influenced by the big players of the chicken industry. However, such independence could create a lack of coordination, making it difficult for farmers to adjust production according to changes in demand. This lack of coordination could lead to uncertain markets for poultry meat and eggs and price fluctuations in the poultry sector in Pakistan (13). Lack of government regulations on price control and uncertain retail markets, as also found by Chaudhry et al. (13), were described to cause high variation in the prices of DOCs and finished chicken products (eggs and meat) throughout the year.

Poor farm management practices were reported in the study that could play a role in AI outbreaks on farms (29, 30). Strict enforcement of control measures such as biosecurity and vaccination at the national level would help to control and manage farm level endemic H9N2 AI outbreaks successfully (31), but no relevant regulation was described by respondents. Farmers also associated the high poultry population density of central and north Punjab (32), and less inter farm distances in poultry rich areas (33) with repeated disease outbreaks in the country. Moreover, live bird market trade patterns and a lack of control over birds' movement (34) was thought to create a niche for pathogens to thrive, resulting in repeated outbreaks of diseases like Newcastle disease virus and H9N2 AI virus infection. These findings highlight important gaps in poultry traceability that could be bridged in the future to devise a successful disease control program. Moreover, disruptions caused by poultry disease may create unfavorable environments for new investments and threaten the survival of small-scale farmers.

Private and public sectors were equally important in controlling poultry diseases including AI at country and farm level. These stakeholders could be targeted to inform policy making and develop robust approaches for disease control (35). The study revealed limited coordination between private and public sector stakeholders providing health services. Partnerships between private and public agencies are highly recommended by the World Organization for Animal Health (OIE) for effective animal disease control, by encouraging rational use of resources especially in lower and middle income countries with limited capital (36). Moreover, such partnerships could create opportunities to expand export markets for fresh, frozen and processed meat, eggs, and their products.

The current study has some limitations. The qualitative nature of the study means that a limited number of participants were interviewed. However, participants were carefully selected because of their extensive knowledge of (parts of) the poultry value chains and to ensure a broad representation of diverse stakeholders. Their views, although believed to be a good approximation of the chains structure and its working, may present some bias. We included participants from large corporate level to small backyard farmers, experienced consultants to farm veterinarians, and large and small poultry traders that helped to cover the major aspects of the poultry sector from wet to processed markets, local, and export markets and disease control options in various poultry settlements. Because of challenges related to social and cultural norms, only one FGD was possible and the remaining data were collected through KIIs conducted face to face. It provided a chance for participants to express their opinions freely. Proportions like market shares, country level shares obtained during data collection were merely based on approximations and personal perceptions of respondents and their average is represented in the results. By-product chains were not explored in depth, but a brief description of various by-products was included.

The mapping gives an in-depth understanding of the structure of the chicken value chains in Pakistan thereby providing a basis for epidemiological disease modeling. Such modeling could help to identify critical control points for interventions toward safe and sustainable food. Identification of actors across various levels of the value chain can be used in further research to investigate personal beliefs and behaviors in relation to control measures. Finally, information on the linkages and processes in these chains provide a starting point for detailed investigation of transaction costs.

CONCLUSION

Detailed value chain maps and information on integrated, independent, and backyard production were used to characterize the chicken industry in Pakistan, and to highlight structural differences between broiler and layer production systems. The analyses revealed the dominance of specific stakeholders, actors and markets in supplying chicken and its products throughout the country. Processed markets were mainly captured by FIBP, PIBP, or PILC where the role of middlemen was negligible, while the wet market was dominated by independent farmers where middlemen influenced the pricing of goods and supplied live birds and eggs to chicken stalls and retail shops. Lack of efficient government policies on price control and farm biosecurity were reported to lead to price fluctuations and inefficient disposal of dead birds. The current study provides baseline information on chicken value chains in Pakistan and identifies factors causing disruptions in the operations of this sector, along with aspects that influence prices. It can be used as a basis for economic impact assessment of chicken diseases and the calculation of economic efficiency of vaccines in different production systems. Stakeholders identified could be targeted for devising policies and novel interventions for efficient control of diseases in the industry.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request from the corresponding author.

ETHICS STATEMENT

Ethical approval was sought from and granted by the Social Sciences Research Ethical Review Board (SSRERB) of the Royal Veterinary College, UK (project reference: URN SR2017-1303). Prior to data collection, informed consent was obtained from all participants for participation in the study, audio recording and photography. The participants provided their written consent to participate in the study.

AUTHOR CONTRIBUTIONS

HA collected, analyzed data, and drafted and revised manuscript. BH and PA were directly involved in developing study design, data analysis, writing of manuscript, and critically reviewed all manuscript drafts. MI contributed toward initial project planning and grant winning (award numbers BBS/E/I/00007034, BBS/E/I/00007035, BBS/E/I/00007038, and BBS/E/I/00007039), technical support in data collection, and reviewed drafts of manuscript. TY contributed toward provision of logistical and technical support while collecting data in Pakistan and reviewed drafts of manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2020.00361/full#supplementary-material

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Understanding the Motivation of Western Java Smallholder Broiler Farmers to Uptake Measures Against Highly Pathogenic Avian Influenza (HPAI)

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Understanding broiler farmers' intention toward highly pathogenic avian influenza (HPAI) control is important to design successful HPAI control programs. We used Theory of Planned Behavior (TPB) to identify factors (i.e., attitude, subjective norm, and perceived behavioral control) associated with the intentions of Western-Java small-scale broiler farmers toward implementing cleaning and disinfection (C&D), vaccination, reporting, and stamping-out without or with 50% compensation. For this, 203 Western-Java farmers were interviewed. The majority of the farmers had a positive intention to implement C&D (89%), reporting (88%), and vaccination (80%). A lower number had a positive intention to join stamping-out both with 50% compensation (67%) and without any compensation (53%). Farmers had a more positive attitude and subjective norm, but lower perceived behavioral control toward one or more of the intentions to implement measures. Attitude was positively associated with intentions to implement C&D and vaccination. Subjective norm of veterinarians of integrated companies was positively associated with intentions to implement vaccination. Perceived behavioral control (i.e., money and time) was positively associated with intentions to implement C&D, vaccination, and stamping-out without any compensation. Results suggest that farmers are in favor of implementing preventive measures (i.e., C&D and vaccination) on HPAI control over facing the consequences of control measures (i.e., stamping-out), and HPAI control programs should primarily focus on incentivizing farmers complemented by programs aiming to improve farmers' attitude. Thus, policy should be emphasized to preventive measures rather than control measures. Financial incentive-based instruments (e.g., price and performance bonus) can be used to increase the intention of farmers to implement C&D and vaccination. Trained vaccinators might help to save the time needed to vaccinate the entire flock can increase the intention of farmers to vaccinate their chickens. Also, informational instruments (e.g., education and communication) can be used to change and to improve the attitude of farmers to implement both measures.

Keywords: poultry farmer, theory of planned behavior, vaccination, biosecurity, highly pathogenic avian influenza, endemic, small-scale, HPAI

INTRODUCTION

Highly pathogenic avian influenza (HPAI) is a zoonotic disease that severely infects both poultry and humans and has a high mortality rate [(1), p. 247]. Highly pathogenic avian influenza has had severe consequences in Indonesia. During a major HPAI outbreak in 2003–2004, many small-scale poultry farmers stopped their farming activities and, as a result, lost their primary source of income [(2), p. 7–8]. Furthermore, there were 200 reported human cases of HPAI leading to 168 casualties (3). Highly pathogenic avian influenza has remained endemic in most Indonesian regions. The number of reported outbreaks of avian influenza (AI) in 2018 reduced to 476, which is five times lower than that in 2007 (4). However, the actual number of outbreaks could be higher because many cases go unreported [(5), p. 8]. Based on this enormous impact, HPAI has been declared a national priority zoonotic disease by the national government since 2005 (6).

Highly pathogenic avian influenza is of particular importance for Western Java, because it has both the largest human and broiler chicken population in the country, accounting for 29% and 6% of the national populations, respectively (7). Highly pathogenic avian influenza has also remained endemic in Western Java to varying degrees across regencies and districts. Local governmental agencies in Western Java control HPAI based on the national HPAI control strategy comprised nine measures: [1] improvement of biosecurity, [2] selective depopulation, [3] vaccination, [4] traffic control, [5] surveillance and monitoring, [6] increasing public awareness, [7] poultry restocking, [8] stamping-out, and [9] monitoring and evaluation (8). Three of these measures are targeted at farms: improvement of biosecurity, routine AI vaccination in an endemic district, and reporting (8). Improvement of biosecurity of broiler farms and AI vaccination have been top-priority programs of the government (9). Stamping-out as a control measure is currently used only in newly infected districts, whereas selective depopulation of infected chickens is implemented in endemic districts. However, the implementation of these control measures has been incomplete and ineffective because of poor infrastructure, the complex structure of the poultry sector, poor incentives for farmers, and budget limitations [(9), p. 1–2]. While biosecurity and vaccination could be implemented by farmers themselves and can even be economically beneficial for farmers, there has especially been a low uptake of HPAI control measures among small-scale commercial and backyard broiler farmers.

It is clear that farmers' behavior is important in the control of HPAI. Currently, there is a lack of understanding of what factors influence the decision of farmers to take up measures against HPAI. Assuming that increased uptake of HPAI control measures among small-scale broiler farmers will aid HPAI mitigation, understanding the factors that influence their motivation to do so is important. Understanding the drivers of broiler farmers is necessary to design HPAI mitigation schemes that are efficient and effective because they have a high likelihood of adoption by farmers. To date, studies on this topic were focused exclusively on sociodemographic characteristics of farmers (10, 11) and farm characteristics (12). A recent study by Indrawan et al. (13) evaluated farmers' characteristics and business types in relation to the implementation of biosecurity measures on broiler farms in Western Java. However, the decision to implement measures against HPAI cannot be explained by sociodemographic and farm characteristics alone. Ajzen (14), through the Theory of Planned Behavior (TPB), states that sociopsychological factors, such as attitude (AT), subjective norms (SN), and perceived behavioral control (PBC), also determine the uptake of a particular action. The TPB states that the intention to perform a behavior is the best predictor of actual behavior (10, p. 179). The TPB has been applied in several studies to gain insight into the psychological factors that influence intentions to take up measures related to animal disease control. Examples include the uptake of rabies vaccination by Indonesian dog owners (15), the uptake of biosecurity measures by dairy cattle farmers in Great Britain (16), and mastitis control by Ethiopian dairy farmers (17). However, no study has used the TPB to evaluate risk mitigation for HPAI. Applying a behavior-explaining framework might shed light on psychological factors of the willingness of farmers to take up different measures against HPAI and consequently might help their implementation.

This article aims to identify (1) if and how psychological factors (i.e., AT, SN, and PBC) of farmers in Western Java are associated with their intention to implement different measures against HPAI and (2) sociodemographic characteristics that affect the farmers' intentions through relations with their AT, SN, and PBC.

MATERIALS AND METHODS

Theoretical Framework

According to the TPB (**Figure 1**), behavioral intention is the best prediction of future behavior (i.e., to perform or not to perform a certain behavior) [(14), p. 179–180]. The theory proposes that a behavioral intention is determined by three psychological factors, namely, AT, SN, and PBC, as shown in **Figure 1** [(14), p. 179–180].

When applying the TPB to the context of changing farmers' behavior regarding HPAI control, AT can be defined as a farmer's beliefs about the outcomes of performing measures against HPAI [i.e., behavioral beliefs (BBs)] weighted by their evaluation of these outcomes [i.e., outcome evaluation (OE)]. For example, farmers who strongly believe and highly value the outcomes of vaccination are expected to have a more positive AT toward vaccination.

Similarly, SN can be defined as a farmer's beliefs on social pressure or other people's opinions about the implementation of HPAI prevention and control measures on their farms (i.e., normative beliefs) weighted by their motivation to comply (MC) with these pressures or opinions (i.e., MC). Influential opinions could originate from technical support (TS) and veterinarians of the integrated company, government veterinarians, TS of animal medicine companies, buyers or customers, broiler farmer peers, family members, neighbors or friends, people who live nearby, and role-model farmers.

Finally, PBC can be defined as a farmer's beliefs about factors such as money, time, and skills required to implement

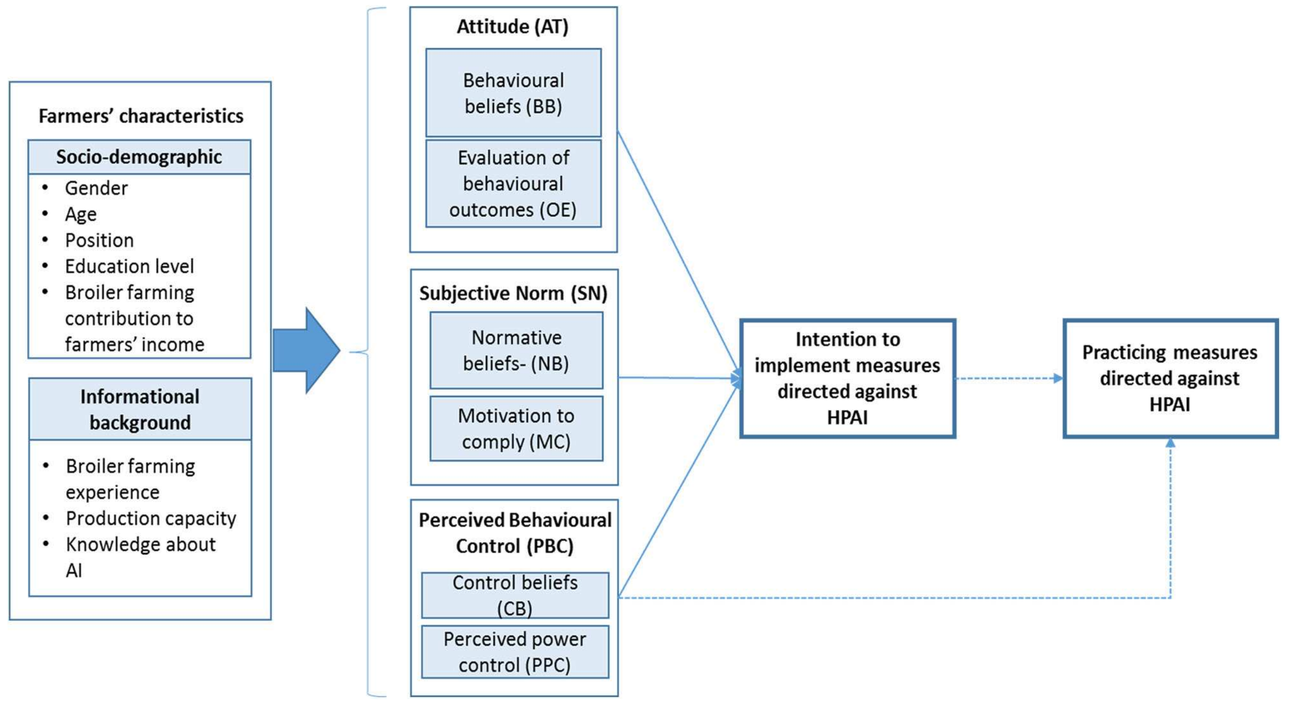

FIGURE 1 | Theory of planned behavior framework for the intention to implement measures against HPAI adapted from Ajzen (14). Dotted lines indicate relationships which are not studied in this article.

HPAI measures [i.e., control beliefs (CBs)], weighted by their confidence in the power of each control factor to facilitate or inhibit the decision to implement the measures [i.e., perceived power of control (PPC)].

Measures Against HPAI at the Farm Level

This article studies the intention of small-scale commercial broiler farmers to implement any of the following preventive, monitoring, and control measures against HPAI: [1] improved biosecurity [i.e., routine cleaning and disinfection (C&D) of the farm area or barn], [2] vaccination, [3] reporting, and [4] stamping-out.

Biosecurity is defined as a set of isolation and sanitation measures with the aim of preventing the introduction as well as the spreading of diseases on the farm. Biosecurity measures will reduce the general risk of avian disease introduction, including HPAI. Ensuring or maintaining the sanitation of the farm, barn, and equipment is recognized as one of the appropriate and practical biosecurity measures on poultry farms (18, 19). In this study, sanitation measures, defined as routine C&D of the farm area or barn for every 2 days, are used as a proxy for biosecurity measures. The term *biosecurity* was not used in interviews with farmers because the term is not well-recognized and is interpreted differently among farmers. Avian influenza vaccination is defined as the implementation of AI vaccination of 7-day-old chickens via subcutaneous injection. This definition was tailored to the Western Java context in which having chickens slaughtered in multiple batches in every rearing cycle is a common practice. Farmers usually start selling their chickens when they are 21–25 days old, and AI vaccines require 14 days to provide sufficient protection from HPAI [(20), 146, p. 18,145–18,146].

Reporting is defined as declaring the observation of HPAI symptoms in one or more chickens to the authority or TS. Surveillance is based on participatory disease surveillance and response due to the lack of surveillance capacity of the veterinary and laboratory services [(21), p. 750]. In theory, reporting is suggested to be an effective early detection tool [(22), p. 435].

Stamping-out is an effective way to eradicate the virus at the source and to prevent further spreading. We included stamping-out in this study because it has been suggested to be effective and efficient in regions with low HPAI endemicity, although the program has been terminated since 2007 [(21), p. 752]. In this study, two scenarios of stamping-out were used, namely, with and without 50% compensation for culled healthy chickens. As such, the approach is adapted to the conditions of limited budgets for HPAI mitigation in Indonesia.

These four measures can be further categorized into two groups based on their scope. Biosecurity and vaccination can be seen as measures that are more in line with the prime interest of farmers for their farm, whereas reporting and stamping-out are in the interest of the sector at large (i.e., as not to be a liability in the farmer community), the government, and the public.

Questionnaire Design

The questionnaire was developed based on the TPB framework and the list of HPAI measures explained above. The questionnaire contained two parts. The first part collected information about farmers' sociodemographic characteristics (e.g., age, education) and farm characteristics (e.g., chicken population). The second part collected information about intentions, AT, SN, and PBC regarding the four measures defined above.

The first part of the questionnaire used multiple-choice, open-ended and closed questions to collect information related to respondents' and farm characteristics, such as age, gender, education, poultry farming experience, chicken population per cycle, awareness of HPAI and its signs, and dependency level on broiler farming. In the second part of the questionnaire, Ajzen's TACT principle, which stands for target, action, context, and time, was used to define intentions. For example, "If HPAI (target) were to occur in the environment where my farm is located (context) within 1 year (time), I would vaccinate all my chickens once in every production cycle on the seventh day (action)." The target and context were used as follows: "If HPAI were to occur in the environment where my farm is located within 1 year" in the sections of BBs, OE, MC, and CBs to emphasize the hypothetical situation to respondents. No additional phrasing was used in the sections of normative beliefs and PPC because these sections are about the opinions of referents and farmers' resources in general.

A five-point Likert scale was used in the second part of the questionnaire. Respondents were asked to state the extent of their agreement/disagreement (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree) to all statements in the sections of intentions, BBs, MC, CBs, and PPC. Respondents were also asked to state the extent of the importance (1 = very unimportant, 2 = unimportant, 3 = neutral, 4 = important, 5 = very important) of all statements in the sections of OE and normative beliefs. The option "do not know" was added to the five-point Likert scale in the normative beliefs section.

Attitude was evaluated by asking respondents about their BBs toward the outcome of implementing each HPAI measure and their subjective evaluation of the importance of different outcomes (OEs). To estimate BBs, respondents were asked about their agreement related to possible outcomes of each measure (e.g., "cleaning and disinfecting my chicken barn every 2 days will reduce the risk of HPAI infection on my farm"). Respondents were also asked to give their subjective evaluation of the importance of outcomes (e.g., "reducing the risk of AI infection on my farm is…"). The following outcomes were included in this study: reduction of HPAI introduction on the farm, prevention of HPAI infection to other chickens in the flock, reducing mortality rate in the flock, prevention of the spread of HPAI to other poultry farms, prevention of HPAI transmission to humans (i.e., high-risk groups), and increase in the likelihood of the farm to be included in stamping-out.

Subjective norms were evaluated by asking respondents about the normative beliefs (NBs) of referents on the importance of implementing HPAI prevention and control measures on their farms (e.g., "according to your knowledge, what is the opinion of your technical support about prevention and control of HPAI?"). Next, respondents were asked about their own MC to the opinions of relevant referents (e.g., "do opinions of your technical support influence you to implement prevention and control of HPAI on your farm?"). If respondents indicated they did not know the opinion of a referent in section NBs, they would not be asked about their MC to the respective referent.

Perceived behavioral control was evaluated based on the resources available to farmers (time, money, and skills) to implement HPAI measures. To measure CBs, respondents were asked to indicate whether implementing the measures is time-consuming, expensive, or difficult (e.g., "implementing HPAI vaccination once in every cycle is expensive"). Then, respondents were asked about their PPC through statements that imply whether respondents perceive they have the necessary skills, spare time, and financial resources to implement measures (e.g., "I can afford to pay the costs for implementing HPAI vaccination once in every cycle").

The questionnaire was first written in English, then translated to Bahasa Indonesia, and translated back to English for verification and publication. The questionnaire was tested in a pilot study. Ten small-scale broiler farmers were interviewed to check their understanding of the statements, as well as their ability to answer the questionnaire. Statements and terminologies that were difficult to understand by the test-farmers were modified.

Data Collection

Survey Location

The poultry sector in Western Java consists of a mix of industrialized (sectors 1 and 2), small-scale commercial (sector 3), and backyard (sector 4) farms; the latter two make up the majority of farms and are widely spread across the region [(23), p. 9]. Small-scale commercial or sector 3 broiler farms keep the chicken inside the barn all the time with low biosecurity [(23), p. 9]. Sector 3 broiler farms are usually located closed or even neighboring to other sector 3 and/or sector 4 poultry farms, as well as to the neighborhood [(5, 23), p. 13].

The survey targeted small-scale commercial broiler farmers or staff in charge of farm management. We selected four regencies as the survey locations (Bogor, Subang, Ciamis, and Tasikmalaya regencies) based on several criteria: broiler chicken population size in Western Java (24); endemic HPAI; different dominant farming schemes (contract, *makloon*, i.e., farmers are paid based on the number of chickens slaughtered, or independent); and operational and logistical factors (i.e., easy access to the regencies, districts, and farms).

Bogor is located south of Jakarta and produces ∼19 million broiler chickens per year at 2,200 broiler farms. Subang is located east of Jakarta with a production of ∼8 million broiler chickens per year at 700 broiler farms. Ciamis is located in the southeast of the Western Java with a production of ∼14.5 million broiler chickens per year at 4,000 broiler farms. Tasikmalaya is located next to Ciamis with a yearly production of 5 million broiler chickens at 1,900 broiler farmers. Subang and Bogor regencies are the main broiler-producing regions where the majority of farms operate under a price contract farming scheme. Ciamis and Tasikmalaya regencies are important producers of broilers where the majority of farms operate under a *makloon* scheme. Currently, there is no region where independent broiler farms are the dominant scheme. They are less and less common, and many such farms have changed to either contract or *makloon*

TABLE 1 | The stratification of samples for each farming scheme in all the regencies.

Regency	Contract	Makloon	Independent	Total
Subang	30 (29)	10 (22)	10 (0)	50 (51)
Bogor	30 (9)	10 (36)	10 (2)	50 (47)
Tasikmalaya	10 (20)	30 (30)	10 (2)	50 (52)
Ciamis	10 (10)	30 (53)	10 (0)	50 (53)
Total	80 (58)	80 (141)	40 (4)	200 (203)

Numbers in the brackets show the number of respondents who completed the interview during the field work.

scheme over the years. Thus, we assumed that the population of independent broiler farms is the smallest in all the regencies.

Sampling

Stratified proportional (random) sampling was used to include sufficient respondents from each farming scheme (i.e., contract, *makloon*, and independent) in the data collection. We aimed to have a total of 200 respondents (**Table 1**), well-beyond the acceptable sample size of 80 with a 50% response rate [(25), p. 29]. The sample size was increased to 220 respondents to account for incomplete interviews. Because integrated companies can change their contract scheme, there are no published data about the number of farms under contract and *makloon* schemes. Thus, stratification by dominant scheme in each of the regencies was based on personal communications with Indonesian poultry experts. That study identified a mix of contract, *makloon*, and independent production systems in every regency, with some of the regencies having either contract or *makloon* as the dominant scheme. For each regency, two to three subdistricts with the highest broiler population were selected as survey locations to make sure the sampling target was achieved within the time and logistic constraints.

The survey was conducted in March 2018 over 8 days; 2 days for each regency. Two survey teams, each consisting of four enumerators, visited each regency at the same time. Each team was deployed in a different subdistrict and was assisted by government officials with knowledge of the area and the local language (i.e., Sundanese). However, the government officials did not join the interview. Upon arrival at the survey location, the enumerators spread out to visit different farms to conduct a farmer or staff member interview. In addition, snowball sampling led to additional respondents after concluding the interview or by asking people who live nearby chicken farms.

The study is exempted from ethics approval from the Social Sciences Ethics Committee of Wageningen University and Research (WUR). However, the survey complies with the rules of data collection and management in WUR and the codes of ethics for research involving human participants in Indonesia. These codes require that participants have to be well-informed about the aims of the research, as well as about the anonymity in collecting and analyzing data [also stated in (26)].

At the start of the interview, all respondents were asked for their consent. Statements were read out loud by the enumerators, and respondents were given a response sheet on which they could pinpoint their response with their finger. The enumerators recorded each response on the questionnaire sheet. All data were analyzed and reported anonymously. In total, we visited 223 small-scale broiler farms. Of these, 20 farmer interviews were not included in the study because farmers were not finished, leaving 203 farmer interviews to be included in the study.

Statistical Analysis

The data were checked for errors and missing values. A descriptive analysis was carried out on farmers' and farm characteristics, the intention to implement the four HPAI measures, and product composites of TPB factors. Product composites were created to measure the three TPB factors (i.e., AT, SN, and PBC) with as little variables per TPB factor as possible. According to the TPB framework (**Figure 1**), the product composite of AT is the product of BB and the corresponding OE. The product composite of SN is the product of normative belief and the corresponding MC. The product composite of PBC is the product of CB and the corresponding PPC. Theoretically, the scores for all product composites range from 1 to 25.

For each of the measures, the internal consistency among the product composites of AT, SN, and PBC was evaluated through Cronbach α. If Cronbach $\alpha > 0.7$, internal consistency among the product composite for that factor was regarded as significant (22, p. 574). For those factors, the product composites were averaged to derive a single direct measure (i.e., mean score) as shown in equations 1 to 3 [(27), p. 405]. When the product composites were inconsistent (Cronbach $\alpha < 0.7$), a subset of product composites within the factor was used to find a combination of product composites that was internally consist. The other product composites were used as separate TPB factors.

$$AT_i = \sum_{j=1}^{n} (BB_j \ x \ OE_j)/n \quad (1)$$

$$SN_i = \sum_{j=1}^{n} (NB_j \ x \ MC_j)/n \quad (2)$$

$$PBC_i = \sum_{j=1}^{n} (CB_j \ x \ PPC_j)/n \quad (3)$$

where i = the TPB factor i; j = the product composite item j; n = the number of items for AT, SN, or PBC.

The data of all the intention variables and TPB factors turned out to be skewed, and thus, logistic regression models were applied to explain the association between the factors and intention. For the logistic regression analyses, intention toward each of the measures against HPAI was divided into two categories based on the Likert scores given for each intention to identify respondents with low or high-level intentions. The responses "strongly disagree," "disagree," and "neutral" were considered to indicate a low-level intention to implement the measure, and the responses "agree" and "strongly agree" were considered to indicate a high-level intention to implement the measure [(28), p. 4,633–4,634; (15), p. 141–142]. The TPB factors were categorized into three levels, based on the distribution of product composites score, in order to identify respondents who had weak, moderate, or strong AT, SN, and PBC. Theory of Planned Behavior factors (i.e., AT, SN, and PBC) that score <12 were considered weak; TPB factors that score ≥ 12 but <16 were considered moderate, and those scoring ≥ 16 were considered strong. If the number of observations in a category was smaller than 15, that category was merged with the nearest other category, resulting in two categories, that is, weak and moderate or moderate and strong. For all the logistic regression analyses using the TPB framework, the categorized intention variables were used as dependent variables, and the categorized AT, SN, and PBC factors were used as independent variables (i.e., one model for each intention). First, a univariable analysis was carried out to check the association between farming scheme and intentions. In this univariable analysis, farming scheme was used as fixed effect, and intention as a dependent variable; however, the analysis did not indicate any associations. Thus, farming scheme was excluded as independent variable in the logistic regression models.

For each of the four control measures, the following univariable and multivariable analyses were carried out. Before conducting multivariable logistic regression, univariable analysis was carried out to examine the association of each TPB factor with intention separately. Theory of Planned Behavior factors with a $p < 0.25$ were included in the multivariable logistic regression (29). Before conducting multivariable analyses, the presence of multicollinearity between TPB factors was checked using Spearman rank correlation coefficients (ρ). The multicollinearity check did not indicate high levels of correlation between TPB factors; all the correlation coefficients (ρ) were <0.8 [(30), p. 224]. Thus, all TPB factors were included in the multivariable analyses.

To evaluate the association of farmers' and farm characteristics with TPB factors, all the background information was included as binary variables in the multivariable logistic regression models. Farmers' and farm characteristics were used as independent variables, whereas TPB factors were used as dependent variables. Independent variables with a $p < 0.15$ by χ^2 test, or by Fisher exact test when there were fewer than five observations in a cell, were included in the multivariable logistic regression analysis.

All multivariable logistic regression analyses were carried out using a backward stepwise procedure. Independent variables that were not significant ($p > 0.05$) were excluded from the models one-by-one at each step. All the statistical analyses were performed using SPSS version 25.0 (31).

RESULTS

Descriptive Statistics

Table 2 provides the descriptive statistics of the sociodemographic and informational background of small-scale broiler farmers interviewed in this study. Of 203 small-scale broiler farmers interviewed, 141 (70%) were *makloon* farmers, 58 (28%) were contract farmers, and four (2%) were independent farmers. On average, participating small-scale broiler farmers were 45 years old, had 10 years of broiler farming experience, and had 3,000 birds on their farm. More than 75% depended on broiler farming activities as their main source of income.

TABLE 2 | Descriptive statistics of sociodemographic characteristics and informational background of small-scale broiler farmers interviewed in this study ($n = 203$).

Sociodemographic characteristics:	Freq. (*n*)	Percentage (%)
GENDER		
Female	18	8.9
Male	185	91.1
AGE		
<45 years	100	49.3
≥45 years	103	50.7
POSITION		
Farm owner	180	88.7
Farm staff	23	11.3
HIGHEST EDUCATION LEVEL		
Elementary	70	34.5
Junior high school	66	32.5
Senior high school and higher education	67	33
INCOME CONTRIBUTION FROM BROILER FARMING		
25–50%	20	9.9
51–75%	67	33
>75%	105	51.7
N.A.	11	5.4
INFORMATIONAL BACKGROUND OF FARMERS		
Broiler farming experience		
≤10 years	128	63.1
>10 years	75	36.9
CHICKEN POPULATION		
≤3,000 birds	95	46.8
>3,000 birds	108	53.2
KNOWLEDGE ABOUT THE EXISTENCE OF AVIAN INFLUENZA		
Yes	155	76.4
No	48	23.6

Table 3 shows the descriptive statistics of intentions to implement HPAI measures. A large proportion of small-scale broiler farmers had a high level of intention to implement C&D (89%), vaccination (80%), and reporting (88%), while a smaller proportion of broiler farmers had a high level of intention for joining stamping-out with (67%) and without (53%) and compensation.

Table 4 shows descriptive statistics and Cronbach α's of the categorized AT, SN, and PBC for each intention. Most broiler farmers (>80%) had a strong SN to the opinions of the referents to implement HPAI prevention and control on their farms. More than half of broiler farmers had a strong AT toward all intentions. In contrast, a relatively low proportion of broiler farmers had strong perceived control over their time and money investments toward C&D, vaccination, and stamping-out.

TPB Factors in Relation to Intentions

Table 5 shows the statistically significant TPB factors for both the univariable and multivariable models for all intentions. Tables with detailed results for all the measures are provided in **Appendices 1–5**. The Nagelkerke R^2 scores suggest that the intentions to implement those HPAI measures that are within the

TABLE 3 | Intentions of broiler farmers interviewed toward implementation of different measures to control HPAI.

Measures	Statements *If within 1 year I know that HPAI exists within the subdistrict of my farm and risk my farm to get infected, therefore…*	*N*	1 SD	2 D	3 N	4 A	5 SA	High intenders (%)[a]
Cleaning and disinfection (C&D)	I will clean and disinfect the barn every 2 days	203	0.5	3.4	7.4	57.6	31.0	89
AI vaccination	I will vaccinate my chickens on the seventh day in every cycle	180	0	6.1	13.9	55.0	25.0	80
Reporting	I will report to the technical support/vet as quick as possible if I observe one of my chickens showing the symptoms infected by AI	203	0	3.9	7.9	55.7	32.5	88
Stamping-out (no compensation)	I will join stamping-out if my farm were found to have an AI outbreak even though I am not given any compensation	173	2.3	17.3	27.2	47.4	5.8	53
Stamping-out (50% compensation)	I will join stamping-out if my farm were found to have an AI outbreak, and I am given 50% compensation for my healthy chickens that would be culled	173	0.6	6.9	26.0	53.8	12.7	67

[a]*Sum percentage of responses with scores 4 (agree) and 5 (strongly agree) for each intention variable.*
SD, strongly disagree; D, disagree; N, neutral; A, agree; SA, strongly agree.

prime interest of broiler farmers (i.e., sanitation and vaccination) are explained better by the model, compared to the intentions for HPAI measures that are more important for public interest (i.e., reporting and stamping-out).

From our models, the AT factor was significantly ($P < 0.05$) and positively related to the intention of broiler farmers to implement routine C&D [odds ratio (OR), 211] and AI vaccination (OR, 20.4). The opinion of veterinarians of the integrated company (OR, 106.1) and the technical adviser from animal health companies (OR, 2.88) were significantly ($P < 0.05$) and positively associated to the intention of broiler farmers to implement AI vaccination and to join stamping-out without any compensation, respectively. The money and time factor were significantly ($P < 0.05$) and positively related to the intention of broiler farmers to implement routine C&D (money: OR, 14.5; time: OR, 9.8), AI vaccination (money and time: OR, 38.4), and to join stamping-out without any compensation (OR, 8.2). None of the TPB factors was significantly ($P < 0.05$) associated with the intention to join stamping-out with 50% compensation in either the univariable or multivariable model.

Farmer and Farm Characteristics in Relation to Significant TPB Factors

Seven sociodemographic farmer characteristics, namely, age, gender, education, poultry farming experience, chicken population per cycle, awareness of HPAI and its signs, and dependency level on broiler farming, were regressed to TPB factors that were statistically significant in the models. Of these seven characteristics, only the contribution of broiler farming to farmers' income was found to be significantly associated with a strong AT toward the intentions to implement C&D and vaccination (**Table 6**). Farmers with a household income derived for 75% or more from broiler farming were more likely to have a strong AT toward C&D (OR, 7.3) and vaccination (OR, 20.2).

DISCUSSION

This study was carried out to gain insight into the psychological factors that determine intentions of small-scale broiler farmers to implement measures against HPAI and to identify sociodemographic characteristics associated with these psychological factors. We applied the TPB that states behavioral intention as a proxy measure of an actual implementation of behavior (14). Our study has several limitations. First, we had an inadequate number of respondents from the group of independent farmers. During the field work, we received information from government officials and other respondents that many independent farmers have closed down their farms or changed to rear male layer chickens. This is because small-scale independent broiler farmers have been experiencing financial losses due to the low market prices of live broiler chickens. In our survey, we tried to get as many independent farmers as possible given the time we had available. The number of independent farmers that we were able to interview was lower than planned. As a consequence, we had more respondents that were price-contract or makloon farmers. Second, in this study, we faced problems with retrieving data on disease or outbreak status of farms, similar to another study that was conducted in the same region (13). The unavailability of the data is because record-keeping is not usual on these farms, and farmers are not aware of the clinical signs of HPAI; hence, only severe HPAI outbreaks will be reported. As a result, information about HPAI is less obvious and trustful. To make sure that farms that had an outbreak in the past were included in our

TABLE 4 | Descriptive statistics and Cronbach α of categorized attitude (AT), subjective norm (SN), and perceived behavioral control (PBC) for all the intentions.

Measures	Variables (AT, SN, PBC)[a]	*n*	Cronbach's α	Weak[b] (%)	Moderate[c] (%)	Strong[d] (%)
Cleaning and disinfection/ sanitation	1. AT (sanitation)	203	0.792	9.4	30.5	60.1
	2. SN[e]					
	i. SN (technical support)	197		—	1.5	98.5
	ii. SN (vet nucleus)	180		—	2.3	97.8
	iii. SN (vet govt.)	170		—	4.7	95.3
	iv. SN (technical support medicine)	155		26.7	—	83.2
	v. SN (friends and role model farmers)	194	0.702	24.7	9.8	65.5
	3. PBC (money)	180		45.6	20.6	33.9
	4. PBC (time)	203		49.3	6.9	43.8
	5. PBC (skill)	203		91.6	8.4	—
Vaccination	1. Attitude (AT)	180	0.863	10.6	23.3	66.1
	2. PBC (money and time)	180	0.718	38.3	27.8	33.9
	3. PBC (skill)	195		63.6	36.4	—
Reporting	1. AT (morbidity and mortality)	203	0.803	—	40.4	59.6
	2. AT (stamping-out risk)	203		14.3	25.1	60.6
Stamping-out (no compensation)	1. AT stamping-out[f]	173	0.809	—	32.4	67.6
	2. PBC (money and time)	173	0.744	54.9	26	19.1
Stamping-out (50% compensation)	1. PBC (money and time)	173	0.709	56.6	25.4	17.9

[a] *AT, attitude; SN, subjective norm; PBC, perceived behavioral control.*
[b] *Weak category: AT, SN, or PBC scores <12.*
[c] *Moderate category: AT, SN, or PBC scores between 12 and <16.*
[d] *Strong category: AT, SN, or PBC scores ≥16.*
[e] *All subjective norms variables were included in univariable analyses for all the five intentions. The significant subjective norm variables were included in multivariable analyses for all the five intentions.*
[f] *Attitude stamping-out was used for both intentions to join stamping-out with no and 50% compensation.*

study, we took a pragmatic approach of sampling, taking into account the involvement of broiler farms that experienced a disease outbreak. Lastly, our study generated a more general understanding of the factors that determine the motivation of broiler farmers, compared to other studies that focus on a specific measure [e.g., (32)]. Since we looked at multiple measures, it was not feasible to probe in extensive detail for each of them in our survey, especially with regard to biosecurity measures that comprise various kinds of measures targeted for different HPAI introduction pathways. However, having four different measures in one study allowed us to identify similarities and differences in factors that influence the motivation of farmers for different measures.

More than 80% of the small-scale broiler farmers were motivated to take up preventive and monitoring measures, such as C&D, vaccination, and reporting. A lower number of small-scale broiler farmers had motivation to join stamping-out either with or without compensation. Our findings suggest that broiler farmers are more willing to take up measures that support their own interests compared to the public interest. The motivation of broiler farmers to implement preventive measures is in line with the preference of the Indonesian government for a vaccination-based HPAI mitigation strategy [(9), p. 7–8].

A large proportion of broiler farmers had a strong AT toward the intentions to implement regular C&D on the farm and vaccination. These findings suggest that broiler farmers had strong beliefs and placed high priorities on the benefits of improving the sanitation of their farm and of implementing AI vaccination for protection of both their poultry and humans from HPAI. The strong AT toward both measures was more likely for broiler farmers who have broiler farming as their main occupation.

For SN, our study showed that only the opinion of veterinarians of the integrated company positively influenced broiler farmers' intentions to vaccinate their chickens. This finding suggests that broiler farmers have a strong belief and MC with the opinion of the veterinarians regarding prevention and control. Clearly, the result came from respondents who were mostly either price-contract or makloon farmers. For independent farmers, TS or veterinarians from an animal health company may replace the role of veterinarians of the integrated company to influence farmers' decision to implement AI vaccination on their farm. However, our findings on SN were based only on a general level (e.g., prevention and control) rather than specifically directed to the measures (e.g., vaccination). Questions or statements that specifically evaluate the opinions of

TABLE 5 | Univariable and multivariable logistic regression model results showing the significant TPB factors for each of prevention, monitoring, and control measures against HPAI.

Variables	Routine C&D	AI vaccination	Reporting	Stamping-out (no compensation)	Stamping-out (compensation)
Attitude (AT)	<0.01[a,b]	<0.01[a,b]	n.s.	n.s.	n.s.
Subjective Norms (SN)					
Farmers	n.s.	n.s.	n.s.	n.s.	n.s.
TS	n.s.	n.s.	n.s.	n.s.	n.s.
Vet nucleus	n.s.	<0.05[a]; <0.01[b]	n.s.	n.s.	n.s.
Vet govt.	n.s.	n.s.	n.s.	n.s.	n.s.
TS medicine	n.s.	n.s.	n.s.	<0.05[a]	n.s.
PERCEIVED BEHAVIORAL CONTROL (PBC)					
Money	<0.01[a]	--	n.a.	--	--
Time	<0.01[a]	--	n.a.	--	--
Skill	n.s.	n.s.	n.a.	n.a.	n.a.
Money and time[c]	--	<0.01[a,b]	n.a.	<0.01[a,b]	n.s.
R^2	0.51	0.47	--	0.17	--

[a]*Univariable model.*
[b]*Multivariable model.*
[c]*Money and time factors were grouped together into a PBC factor (Cronbach α >0.7).*
n.s., not significant; n.a., not applicable.

TABLE 6 | Multivariate logistic regression model results describing the association of sociodemographic characteristics of broiler farmers with TPB factors that were significantly associated with the intentions.

Measures	Background factors	TPB factors	Level	OR (95% CI)
Cleaning and disinfection (C&D)	Income contribution	Attitude	≥75%	12.1 (2.11–69.39)**
			50–<75%	4.55 (0.78–26.61)
			25–<50%	ref.
Vaccination	Income contribution	Attitude	≥75%	20.24 (3.48–117.71)**
			50–<75%	2.36 (0.52–10.61)
			25–<50%	ref.

[a]*Odds ratio.*
[b]*Reference category.*
[c]*95% confidence interval.*

others about a specific measure against AI might better explain the effect of SN on the intention of farmers to implement specific measures.

For PBC, being in control of the consequences for time and income significantly determined the intentions of farmers to implement C&D measures and AI vaccination. Perceived behavioral control is more likely to determine the intentions of broiler farmers when they have less control over the consequences of implementation. For example, the OR of PBC for vaccination is higher than the PBC score for C&D. In this case, PBC might serve as a safety net for broiler farmers in case the consequences of the implementation of a measure are uncontrollable or beyond the expectation of the farmers. The significant associations between PBC and intentions also suggest that broiler farmers perceive those measures as costly and laborious. Despite this perception, they are still willing to spend their money and time on their implementation. Thus, broiler farmers who have more financial resources and spare time are more likely to clean and disinfect their farm more frequently and to vaccinate their chickens.

The significant association between AT and the intention to implement preventive measures suggests that there is room to develop relevant informational policy instruments. Informational instruments, such as providing practical information, could increase the internal motivation of farmers to perform specific behaviors [(32), p. 118]. To increase the adoption of HPAI control measures, practical information should be suited to the local context and promote financial benefits from implementation [(33), p. 530; (34), p. 11–12]. Training programs about prevention and control of HPAI, can be used by the government to increase the knowledge and awareness about HPAI and measures to control it. Training programs are already a priority supportive measure of the Indonesian government, but it is unclear how effective these programs are to actually increase knowledge and awareness about HPAI. The dissemination of the information in the training, in this case, should be done via credible communicators who are perceived by broiler farmers to be trustworthy and to have a high level of "similarity" [(32), p. 118], using education and communication materials developed by veterinarians, both public and private, and small-scale broiler farmers [(33), p. 530].

For HPAI mitigation in Indonesia, veterinarians of the integrated company would be better communicators than government-hired veterinarians. Because of high turnover, veterinarians hired by the government usually have less experience in working and communicating with broiler farmers compared to veterinarians from large integrators. Thus, the latter are more appropriate communicators when it comes to HPAI mitigation because they usually have more field experience and, more importantly, understand the local context better than government-hired veterinarians. Local governments could strengthen the communication with broiler farmers through farmer extension services, for instance, a periodic training and assistance program that are targeted to farmers and farm workers. This suggests that local governments should extend their current public–private partnership program by involving veterinarians from large integrators to raise the awareness of the importance of preventive measures among small-scale broiler farmers.

The finding that economic and time factors influence broiler farmers' intention to implement routine C&D and vaccination suggests that financial incentives and time-saving prevention and control scenarios will increase broiler farmers' motivation to implement those measures. These are basically economic elements. Furthermore, our study also found that the more broiler farmers are dependent on their broiler farm as their main source of income, the more likely they have positive AT toward routine C&D and vaccination measures to prevent HPAI. These findings suggest that programs that incentivize broiler farmers to increase their biosecurity and vaccinate their chickens may be helpful. Financial incentives in the form of a bonus on the market price and/or on performance could be applied as instruments to increase the uptake and the continuity of the implementation of biosecurity [(35), p. 599]. The same incentive could also be applied for vaccinated chickens. Moreover, vaccination may also be stimulated by reducing the costs of vaccination by a subsidized vaccine or assistance with vaccination, as is done for backyard poultry farms. However, because we do not know the economic impact of routine C&D and vaccination, we could not identify the exact incentives that would be suitable for broiler farmers in this case. Further research is needed to identify appropriate economic incentives for broiler farmers who implement vaccination and biosecurity measures on their farm.

CONCLUSIONS

This study clarifies that small-scale broiler farmers are more in favor of preventive measures compared to monitoring and control measures directed against HPAI. Furthermore, our findings suggest that factors, such as broiler farmers' AT, opinions of veterinarians of nucleus company, and broiler farmers' financial and time resources, were positively associated with one or more of broiler farmers' intentions to implement preventive and control measures against HPAI. Our results also suggest that informational and financial instruments are appropriate instruments to increase the uptake of prevention and control measures by small-scale broiler farmers and could help mitigate HPAI spread in Western Java.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MP designed the study, collected and analyzed the data, and drafted the manuscript. The remaining authors provided input on the design of the study, helped in interpreting study results, and critically revised the manuscript. All authors read and approved the final manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2020.00362/full#supplementary-material

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Modeling Economic Effects of Vaccination Against Porcine Reproductive and Respiratory Syndrome: Impact of Vaccination Effectiveness, Vaccine Price, and Vaccination Coverage

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Porcine reproductive and respiratory syndrome (PRRS) causes substantial financial losses in pig farms and economic losses to societies worldwide. Vaccination against PRRS virus (PRRSV) is a common intervention in affected farms. The aim of this study was to assess the economic impact and profitability of potential new PRRS vaccines with improved efficacy at animal, herd, and national level. Two vaccination strategies were modeled; (i) mass vaccination of sows only (MS) and (ii) mass vaccination of sows and vaccination of piglets (MSP), comprising different scenarios of vaccine effectiveness, vaccine price, and vaccination coverage. A farrow-to-finish farm with 1,000 working sows from a pig-dense region in Germany served as an example farm. Financial benefits were obtained from gross margin analyses and were defined as difference in gross margin between a PRRSV-infected farm without vaccination (baseline) and with vaccination (intervention). Financial benefits were highest if both sows and piglets (MSP) were vaccinated. In these scenarios, median annual net benefits per working sow ranged from €170 to 340. If sows only were vaccinated (MS), estimated benefits attributable to vaccination were between €148 and 270. Decisive variables for the estimation of national level benefits were the number of farmers switching from existing to a better protecting vaccine, the number of previously non-vaccinating herds adopting the new vaccine, and the effectiveness of the new vaccine relative to those already available. Benefits were greatest when the new vaccine was adopted by previously non-vaccinating herds. The analyses showed that vaccination against PRRS was beneficial for all modeled scenarios. The magnitude of benefits derived from vaccination was more susceptible to changes in vaccination effectiveness than to vaccine price changes. This study provides evidence to support future vaccine development. The estimates indicate that the introduction of more efficient vaccines might lead to substantial financial benefits, is of socio-economic importance and that new vaccines might significantly contribute to the reduction of disease burden.

Keywords: economic modeling, pig production, disease intervention, PRRS control, vaccination effectiveness

INTRODUCTION

Porcine reproductive and respiratory syndrome (PRRS) causes substantial economic losses in pig production worldwide (1–4). In the United States, the estimated annual cost of PRRS on the national level was estimated at US $664 million, based on a population size of 5.8 million breeding sows and 110 million pigs marketed per year (2). At farm level, costs due to PRRS depend on the individual farm situation including factors such as disease severity, affected production stages, or farm size. Median losses in a farrow-to-finish farm in Germany with 1,000 working sows moderately affected in all production stages were estimated at € 442′973 per year (3). Both the reproduction component of the disease manifested in breeding sows and the respiratory component in growing pigs contribute substantially to the economic losses (2, 3).

Various strategies have been developed to control PRRS. Apart from elimination procedures with the aim to create a completely virus-negative herd (e.g., closure and roll-over) or improvement of biosecurity and management, vaccination against PRRS is a common approach to control the disease (5). Depending on individual farm situation, several intervention strategies have shown to be profitable, with mass vaccination of sows or mass vaccination of sow and piglets being amongst the most cost efficient control strategies (6).

Besides the commercially available inactivated vaccines and modified-live virus vaccines (MLV), new techniques for administration have been explored and developed and research on the use of DNA vaccines to further improve efficacy of MLV vaccines has been conducted (7–9). However, current vaccines fail to provide complete protection against heterologous field strains and commercially available vaccines only partially prevent or mitigate the disease and show limited effectiveness in the field (10–13).

Most literature on vaccine efficacy describes effects under ideal study conditions. Typically, vaccine efficacy is assessed in experimentally infected pigs and refers to clinical, virological, or pathological findings after challenge under experimental conditions. Outcomes are reported as reduction of viremia in terms of duration and/or magnitude, of clinical signs or of pathological lesions (11, 14). Moreover, vaccine effectiveness might also be considered by epidemiological parameters describing disease dynamics and a reduction in virus transmission (15, 16).

Literature on vaccination effectiveness in the field and the impact on production parameters is scarce (17). However, this information is needed for farmers to convert positive effects of vaccination into monetary values and to estimate financial benefits through economic assessments and gross margin analyses (18). Moreover, the benefit of a vaccine in relation to its cost and thus vaccine price and return on investment are determining factors that influence farmer's attitude and willingness to pay for a vaccine (19). When trying to estimate financial benefits on a national level, these are important aspects, which might affect vaccination coverage and the proportion of farmers adopting a new vaccine. With these preconditions, scenario modeling and stochastic simulations are common approaches used to account for missing information and uncertainty.

The aim of this study was to assess economic effects associated with vaccination against PRRS and to estimate financial benefits on animal, herd, and national level. To evaluate the impact of various vaccine characteristics, different levels of vaccination effectiveness, vaccine price, and vaccination coverage were modeled.

MATERIALS AND METHODS

Model Description

The economic assessment of vaccination against PRRS is based on a stochastic model developed by Nathues et al. (3). The initial model estimated the financial burden of disease in endemically PRRSV-infected farms and served as baseline to model the economic efficiency of different control strategies against PRRS (6). To estimate the potential financial benefit of different vaccine characteristics and vaccination scenarios within this project, the initial model was adapted and expanded accordingly. The model was built in Excel (Microsoft Corporation, Redmont, Washington, USA) and the Add-on @Risk was used (Palisade Corporation, Newfield, New York, USA) to account for uncertainty and variability of parameters. The spreadsheet model consisted of several sub-models, which were linked with each other. Production parameters and epidemiological effects were identified and assessed in a literature review and implemented into the initial model. The production model simulated production dynamics within a timeframe of one year. The epidemiological flow model simulated disease impact according to defined disease status and incorporated these effects into the production model. In the intervention model, the cost and effectiveness associated with different vaccine characteristics and intervention strategies were defined and linked with the production and epidemiological model. The economic impact of disease and intervention was assessed by performing a gross margin analysis using production model outputs. The gross margin was defined as the total revenue minus variable cost. Variable cost consisted of replacement cost, market prices for sold or slaughtered animals, feeding cost, veterinary cost, cost for disposal of dead animals, variable energy cost, and miscellaneous cost. Full details of the baseline model, including prices of economic parameters, can be obtained from Nathues et al. (3) and the **Supplementary Material**. Stochastic simulations were run with 1,000 iterations per scenario. For the most part, stochastic model outputs were not normally distributed and estimates are, unless stated otherwise, reported as medians.

Farm Description

To model economic effects at farm-level, a typical farrow-to-finish farm from a pig-dense region in Germany was chosen to serve as an example farm. As this farm type contains all three production stages (breeding, nursing, and fattening), it was possible to capture financial effects for each of the three production parts separately. Furthermore, this approach permits that the model could also be used for economic evaluations of farms that only have one or two of the production parts (i.e.,

TABLE 1 | Farm characteristics of the example farrow-to-finish farm used for the economic model.

Parameter	Value
Number of working sows	1,000
Production rhythm (weeks)	3
Duration of suckling period (weeks)	3
Replacement rate (%)	35
Feed consumption during gestation (kg)	275
Feed consumption during lactation (kg)	200
Downtime between turns in nursery pens (days)	2
Downtime between turns in fattening pens (days)	5
Weight after nursery (kg)	30
Weight at slaughter (kg)	120

TABLE 2 | Production parameters with assumed values of a PRRS negative farm and a PRRSV-infected farm with corresponding absolute disease effects.

Parameter	Negative farm	Infected farm	Disease effect
Return-to-oestrus rate	10.0%	13.5%	+3.5%
Abortion rate	2.0%	3.9%	+1.9%
Average piglets born alive per sow and litter	12.7	11.4	–1.3
Pre-weaning mortality	11.0%	13.5%	+2.5%
Weight at weaning	6.0 kg	5.5 kg	–0.5 kg
Days in nursery	45 days	50 days	+5 days
PRRS morbidity in weaners	–	20.0%	+20.0%
Mortality in weaners	3.0%	10.0%	+7.0%
Days in fattening	119	127 days	+8 days
PRRS morbidity in fatteners	–	20.0%	+20.0%
Mortality in fatteners	1.5%	3.0%	+1.5%

breeding herd with the sale of weaners, breeding herd with the sale of nursery pigs, nursery only, fattening only). The example farm has 1,000 working sows, batch-wise farrowing every week, 3 weeks suckling period, an annual replacement rate of 35%, and finishers are sold at 120 kg live weight. A detailed description of farm characteristics is listed in **Table 1**. For the disease impact estimation, it was assumed that field virus was newly detected in a farm endemically infected with PRRSV. The farm previously did not vaccinate against PRRS and both reproduction and respiratory components of the disease were present in the herd. Consequently, it was expected that clinical effects would occur in all production parts along with reduced performance and production output in breeding, nursing, and fattening. Values of production parameters of a PRRS negative farm, a PRRSV-infected farm, and absolute disease effects are listed in **Table 2**. Negative farm data was obtained from industry reports (20, 21) whereas information on the magnitude of disease effects in endemically PRRSV-infected farms was assessed through an expert poll conducted within the study framework of the initial model (3). Out of various scenarios with different levels of disease severity described in the initial model, a moderate scenario with median values for clinical affectedness was selected to serve as basis for the conducted analyses.

Vaccination Strategies and Vaccine Characteristics

Two different vaccination strategies were considered in the model: (i) mass vaccination of sows only (MS) and (ii) mass vaccination of sows and vaccination of piglets (MSP). For MS, the vaccination protocol comprised a basic immunization of all sows and a booster vaccination 4 weeks later. After this, the entire sow herd is periodically vaccinated every 3 month. Incoming gilts are vaccinated twice during acclimatization. The MSP strategy is following the same protocol as the MS but with additional vaccination of piglets between the ages of 2–3 weeks.

The two main vaccine characteristics and associated economic effects examined in this study were vaccination effectiveness and vaccine price. For the economic modeling, the vaccination effectiveness was defined as the proportion by which disease effects in production parameters would be reduced after vaccination. Thus, related data on the improved of production output was required for implementation into the production model. The effectiveness of a vaccine when deployed in the field depends not only on the vaccine efficacy under ideal conditions but also on the characteristics of the population to whom it is administered and the comparison population (14). Since no evidence-based data was available, different levels of vaccination effectiveness were modeled: 50, 60, 70, 80, and 90%. In this context, an assumed vaccination effectiveness of 80% would mean the following: If the baseline abortion rate in a PRRS negative farm is 2% and in a PRRSV-infected farm 3.9%, the absolute disease effect is +1.9% (**Table 1**). Vaccination would reduce disease effects by 80% (−1.52%) and the abortion rate would persist at 2.38% after vaccination. To account for uncertainty and variation of vaccine price, several scenarios with different price levels were modeled: €0.75, 1.00, 1.25, and 1.50. The vaccine price was defined as the price per dose (including labor) for the single vaccination of one sow. For the MSP strategy, vaccination of a piglet would cost 80% of the price of sow vaccination.

National-Level Analyses and Vaccination Coverage

The estimation of national-level benefits was based on outcomes from farm-level analyses. Demographic data on the pig population in Germany was obtained from the Federal Statistical Office (22). Overall, there are 27.2 million pigs, located on 23,800 farms. Of these, 8,400 farms hold breeding sows with totally 1.9 million sows. Herd-level prevalence show regional differences and is estimated to be between 50 and 100%, with high prevalence particularly in pig dense regions (23).

For the analyses, the breeding sow population was divided into two groups: previously vaccinated sows (preVS) and previously non-vaccinated sows (pnonVS). Previously vaccinated sows were defined as sows that were vaccinated against PRRS with a licensed and commercially available vaccine in the past. On the other hand, pnonVS were defined as sows that were not vaccinated against PRRS yet. The proportion of preVS is equivalent to the initial vaccination coverage whereas the proportion of pnonVS is equal to one minus the vaccination coverage. No empiric data on vaccination coverage was available and consequently different levels of preVS and pnonVS were modeled to account for uncertainty of this parameter. The proportion of sows that were vaccinated with a potential new vaccine (nVac) was independent from vaccination coverage and could be different in preVS and pnonVS. In preVS, it described the switch from a previously used licensed vaccine to nVac, whereas in pnonVS it described the switch from not vaccinating sows to newly vaccinating sows using nVac.

Different levels of vaccination effectiveness were modeled in the national-level analyses. For pnonVS, these comprised 50, 60, 70, 80, and 90%. For preVS, vaccination effectiveness of nVac was expressed as absolute change in effectiveness and five levels were considered (+5, +10, +15, +20, and +25%). For example, an effectiveness of +5% implied that disease effects were reduced by an additional 5%, compared to the previously used vaccine. To estimate financial benefits at national level, individual benefits per breeding sow were extrapolated. Animal-level benefits used as input values were obtained from farm-level analyses and were then multiplied by the corresponding number of affected animals. For national-level analyses, vaccine price was fixed at €1 for all scenarios.

RESULTS

Financial losses due to PRRS, expressed as difference in gross margin between a PRRSV negative and a PRRSV-infected farrow-to-finish farm with disease effects according to **Table 2** and 1,000 working sows were €400,018 per year (**Figure 1**). The median farm-level financial benefit attributable to vaccination with nVac ranged from €147,525 to 269,759 when sows only are vaccinated (**Table 3**) and from €169,563 to 339,643 in the MSP strategy, when piglets are also vaccinated (**Table 4**). Consequently, annual animal-level benefits per working sow attributable to vaccination were estimated to be between €148 and 270 for MS (**Figure 2**) and between €170 and 340 for MSP (**Figure 3**). These two figures give an overview of the associations between the modeled vaccine characteristics and financial benefits per working sow. The magnitude of financial benefits generated was more sensitive to a change in vaccination effectiveness than the variation of vaccine price. Particularly

TABLE 3 | Differences in annual gross margin (in €) between a PRRSV-infected farm without intervention and a PRRS-infected farm with mass vaccination of sows (MS).

Vaccine price	Vaccination effectiveness				
	50%	60%	70%	80%	90%
€0.75	150′727	179′865	209′149	239′455	269′759
€1.00	149′581	178′387	208′127	238′336	268′272
€1.25	148′313	177′482	207′020	237′136	267′480
€1.50	147′525	176′312	205′959	235′820	266′435

TABLE 4 | Differences in annual gross margin (in €) between a PRRSV-infected farm without intervention and a PRRSV-infected farm with mass vaccination of sows and piglets (MSP).

Vaccine price	Vaccination effectiveness				
	50%	60%	70%	80%	90%
€0.75	188′938	225′481	262′646	300′798	339′643
€1.00	182′137	218′858	255′985	293′787	332′766
€1.25	175′883	211′992	249′089	287′053	325′839
€1.50	169′563	205′473	242′660	280′265	319′222

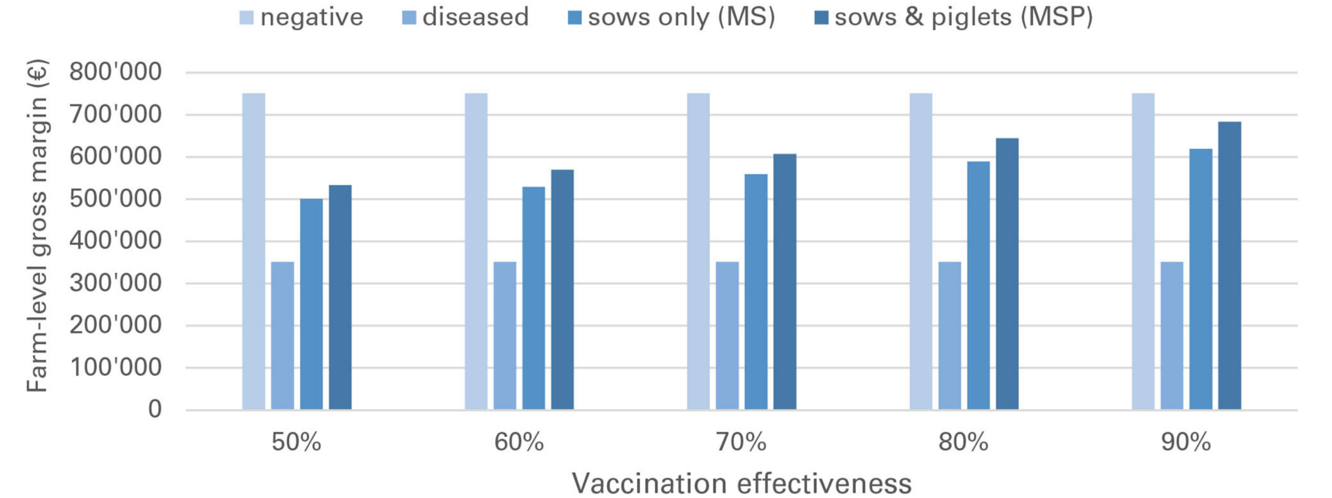

FIGURE 1 | Annual gross margins for a PRRS negative farm, a PRRSV-infected farm without vaccination ("diseased") and a PRRSV-infected farm with vaccination (MS and MSP strategy).

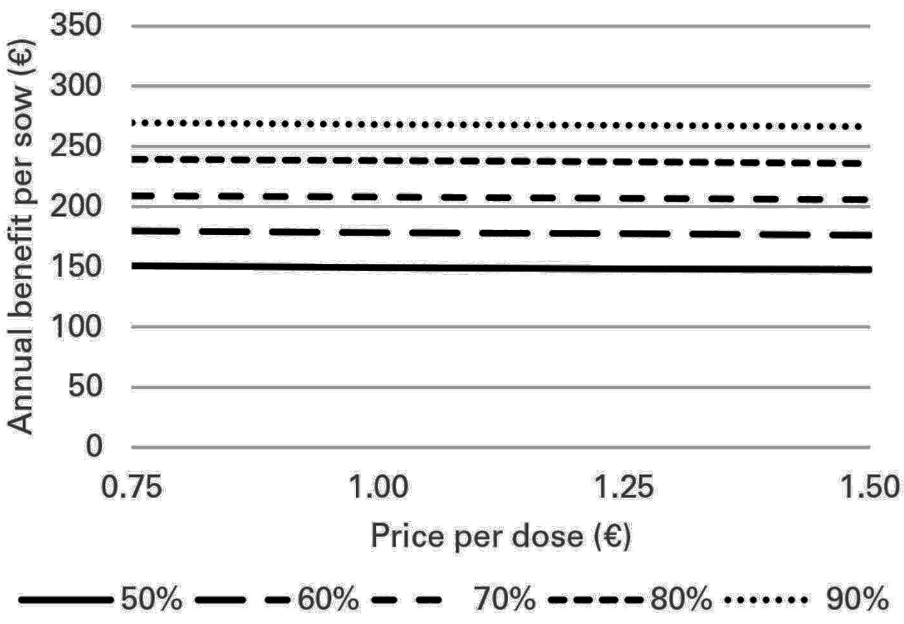

FIGURE 2 | Annual benefit per working sow, depending on vaccination effectiveness, and vaccine price, when vaccinating sows only (MS strategy) against PRRS.

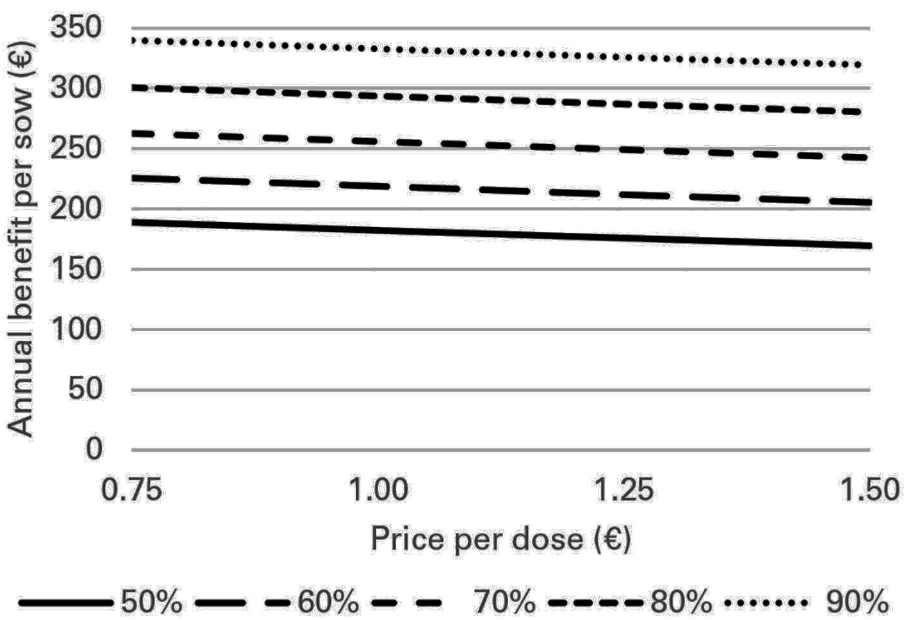

FIGURE 3 | Annual benefit per working sow, depending on vaccination effectiveness, and vaccine price, when vaccinating sows and piglets (MSP strategy) against PRRS.

in the MS strategy, vaccine price had only minor effects on the profitability, whereas effects were more pronounced when piglets are vaccinated as well. For all modeled scenarios, the MSP strategy was more beneficial than MS when identical vaccine characteristics were assumed.

Financial benefits at national level were generated by adopting nVac to both preVS and pnonVS. Outputs were dependent on the variation of vaccination effectiveness, vaccination coverage, and the proportion of sows newly vaccinated with nVac.

In preVS, for each sow newly vaccinated with nVac, a median benefit of €3 was gained for every +1% of increased effectiveness compared with the effectiveness of the previously used vaccine. National-level financial benefits ranged from €2.3 to 45.7 million for the listed scenarios and a fixed vaccination effectiveness of +10% (**Table 5**). As an example, if 30% of sows were newly vaccinated with nVac and vaccination coverage was 60%, the annual financial benefit was estimated to be €10.3 million. If vaccination coverage was fixed at 60% and vaccination effectiveness varied from +5 to +25%, the financial benefit ranged from €1.7 to 85.8 million (**Table 6**). The proportion of sows newly vaccinated with nVac had a substantial effect on the magnitude of financial benefit, especially when effectiveness increased (**Figure 4**).

In pnonVS, financial benefits per sow were substantially higher than in preVS. Median benefits per sow ranged from €150 to 268, depending on vaccination effectiveness and at a fixed vaccine price of €1. Already a small number of pnonVS newly vaccinated with nVac generated significant benefits at national level. If vaccination effectiveness varied between 50 and 90% and between 1 and 10% of sows were vaccinated with nVac, financial benefits ranged from €2.9 to 51.1 million (**Table 7**). If initial vaccination coverage was 50% and all of the pnonVS would newly be vaccinated with nVac, financial benefits would range from €143 to 256 million, depending on vaccination effectiveness (**Figure 5**).

TABLE 5 | Financial benefits (in €) associated with vaccination of previously vaccinated sows (preVS), when vaccination effectiveness of a potential new vaccine (nVac) is +10% compared to the previously used alternative vaccine.

Proportion of nVac in preVS	Vaccination coverage				
	40%	50%	60%	70%	80%
10%	2′287′440	2′859′300	3′431′160	4′003′020	4′574′880
20%	4′574′880	5′718′600	6′862′320	8′006′040	9′149′760
30%	6′862′320	8′577′900	10′293′480	12′009′060	13′724′640
40%	9′149′760	11′437′200	13′724′640	16′012′080	18′299′520
50%	11′437′200	14′296′500	17′155′800	20′015′100	22′874′400
60%	13′724′640	17′155′800	20′586′960	24′018′120	27′449′280
70%	16′012′080	20′015′100	24′018′120	28′021′140	32′024′160
80%	18′299′520	22′874′400	27′449′280	32′024′160	36′599′040
90%	20′586′960	25′733′700	30′880′440	36′027′180	41′173′920
100%	22′874′400	28′593′000	34′311′600	40′030′200	45′748′800

Estimates depend on vaccination coverage and the proportion of preVS that are newly vaccinated with nVac.

TABLE 6 | Financial benefits (in €) due to vaccination of previously vaccinated sows (preVS) with nVac instead of a previously used licensed vaccine (vaccination coverage fixed at 60%).

Proportion of nVac in preVS	Vaccination effectiveness				
	+5%	+10%	+15%	+20%	+25%
10%	1′715′580	3′431′160	5′146′740	6′862′320	8′577′900
20%	3′431′160	6′862′320	10′293′480	13′724′640	17′155′800
30%	5′146′740	10′293′480	15′440′220	20′586′960	25′733′700
40%	6′862′320	13′724′640	20′586′960	27′449′280	34′311′600
50%	8′577′900	17′155′800	25′733′700	34′311′600	42′889′500
60%	10′293′480	20′586′960	30′880′440	41′173′920	51′467′400
70%	12′009′060	24′018′120	36′027′180	48′036′240	60′045′300
80%	13′724′640	27′449′280	41′173′920	54′898′560	68′623′200
90%	15′440′220	30′880′440	46′320′660	61′760′880	77′201′100
100%	17′155′800	34′311′600	51′467′400	68′623′200	85′779′000

DISCUSSION

Results from this study demonstrate that the introduction of nVac is associated with substantial financial benefits at animal, farm, and national level.

When interpreting farm-level outcomes it has to be considered that the estimated benefits are reported as differences in gross margin between a PRRSV-infected herd without previous intervention and a PRRSV-infected herd with intervention, in the form of vaccination. Furthermore, it was assumed that all production parts were affected by PRRS, which was associated with substantially reduced production performance and farm output and thus farm revenue. Therefore, it has to be taken into account that in practice it is likely that a farm showing such magnitudes of disease effects would already have implemented some sort of disease control, possibly in the form of vaccination with an already licensed and commercially available vaccine. This would imply that financial benefits of using nVac would have to be obtained from comparing farms vaccinating with nVac and farms vaccinating with an "old" vaccine. Consequently, reported estimates represent the maximum possible benefits based on the situation when no previous disease control was established. Financial benefits in farms that switch from an alternative vaccine to nVac are less pronounced, as demonstrated in the national-level models.

Estimates from this study are based on an example farm where both reproductive and respiratory traits were affected by PRRS. The reproduction parameters "abortion rate" and "number of piglets born alive" had a significant impact on gross margin. When an increased number of piglets are born due to improved reproductive performance after vaccination, more pigs go through the different production stages and eventually more fatteners are sold for slaughter. This had a direct impact on the farm output and consequently led to higher farm revenue. A main effect of the respiratory component of the disease is the reduced performance of growing pigs (24, 25). This effect is also reflected in the finding that the MSP strategy is more profitable than the MS. The additional cost for the piglet vaccination was compensated and surpassed by the improved production performance in the nursery and fattening stage.

The sensitivity analysis showed that the gross margin and associated economic profitability were more sensitive to vaccination effectiveness than to vaccine price. However, the range of vaccine prices included in the scenarios was limited. A potential novel vaccine stands in competition with other PRRS vaccines (7) and therefore its price would be influenced by the price of the already commercially available vaccines. Furthermore, it is likely that vaccination effectiveness and vaccine price are correlated. If vaccination effectiveness is high, farmers might be willing to pay more and when farmers can chose between different products, they would only purchase vaccines that are more expensive if vaccination effectiveness is increased

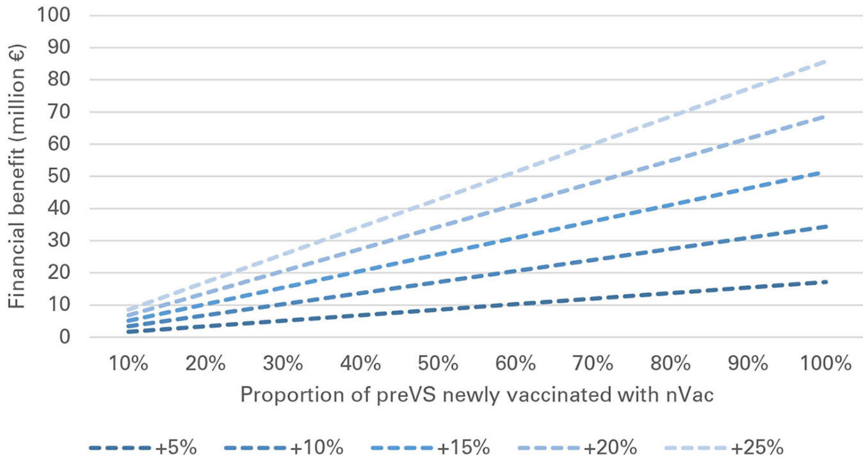

FIGURE 4 | Financial benefit associated with vaccination of previously vaccinated sows (preVS), when vaccination coverage is 60%, and vaccination effectiveness of nVac ranges from +5 to +25%.

TABLE 7 | Financial benefits (in €) associated with vaccination of previously non-vaccinated sows (pnonVS) for different levels of vaccination effectiveness and proportion of newly vaccinated sows.

Proportion of sows vaccinated with nVac	Vaccination effectiveness				
	50%	60%	70%	80%	90%
1%	2′851′317	3′400′409	3′967′309	4′543′155	5′113′805
2%	5′702′634	6′800′818	7′934′618	9′086′310	10′227′609
3%	8′553′951	10′201′228	11′901′928	13′629′465	15′341′414
4%	11′405′267	13′601′637	15′869′237	18′172′620	20′455′219
5%	14′256′584	17′002′046	19′836′546	22′715′776	25′569′023
6%	17′107′901	20′402′455	23′803′855	27′258′931	30′682′828
7%	19′959′218	23′802′864	27′771′165	31′802′086	35′796′633
8%	22′810′535	27′203′273	31′738′474	36′345′241	40′910′437
9%	25′661′852	30′603′683	35′705′783	40′888′396	46′024′242
10%	28′513′168	34′004′092	39′673′092	45′431′551	51′138′047

accordingly (26). Overall, a "vaccine cost-benefit ratio," expressed as vaccine price compared to its vaccination effectiveness, could serve as key criteria in farmer's decision-making process. This implies that even if the vaccination effectiveness of nVac would be lower than the effectiveness of alternative vaccines, farmers might still switch to nVac under certain circumstances. Consequently, setting a market price for nVac without knowing its effectiveness in the field would be associated with a high level of uncertainty and thus different scenarios were modeled. In addition, market prices of vaccines do not only depend on its effectiveness alone, but do include many other criteria and are defined in a multi-step procedure (27) which implies that vaccine prices used in this model do not permit conclusions about production cost or margins of the vaccine manufacturer.

The results indicate that benefits generated in pnonVS are significantly higher than in preVS. This is because infected pnonVS showed substantially reduced production performance prior to vaccination whereas disease effects in preVS were already diminished due to vaccination with an alternative vaccine. However, the contribution to the overall financial benefit might still be larger from preVS than from pnonVS. It is likely that in practice, the proportion of sows newly vaccinated with nVac might be substantially higher in preVS than in pnonVS. It might be more challenging to convince farmers to start vaccinating their sows against PRRS (and chose nVac) than convincing farmers that already have been vaccinating their sows to switch to nVac. These farmers are already familiar with PRRS vaccination, associated cost, labor, and equipment and thus might be more likely to start using a new vaccine (28). A further point for discussion is the impact of nVac on the market equilibrium, associated with reduced disease prevalence (29). If a large proportion of farmers were vaccinating their sows, production performance would increase, more pigs would be marketed and eventually supply increases. This would lead to a shift of the supply curve and a change of market equilibrium associated with lower prices for farmers (30). However, market impacts were not considered in this study.

In the context of scenario analysis, reported financial benefits for different scenarios modeled in this study do not consider the plausibility of the corresponding scenario. The likelihood of a certain scenario has to be further investigated and supported with empiric data as no information on current vaccination coverage or public data on market shares of existing PRRS vaccines is available. Moreover, without yet knowing vaccination effectiveness and vaccine price, it is difficult to estimate to what extent nVac would be adopted in the field. The proportion of farmers that would switch from an alternative vaccine to nVac, as well as the proportion of farmers who would newly start vaccinating against PRRS, significantly depend on these key vaccine characteristics. Therefore, potential socio-economic benefits largely depend on farmers' attitude toward PRRS vaccination and their decisions with respect to switching to a new vaccine (31). The behavior of a few single farmers might have a significant impact at national level, depending on their farm size. In Germany, farm sizes are rather heterogeneous (22). There are

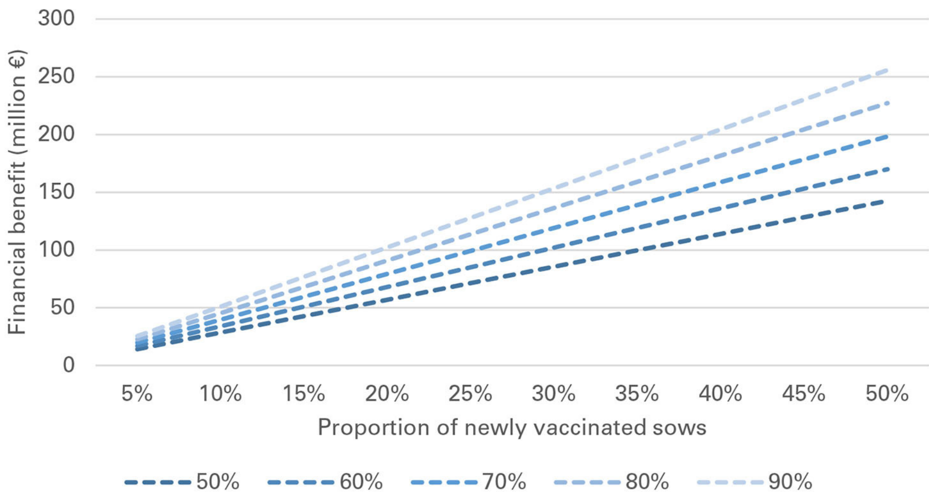

FIGURE 5 | Financial benefit associated with vaccination of previously non-vaccinated sows (pnonVS) for different levels of vaccination effectiveness and proportions of newly vaccinated sows.

many small farms and only few large pig farms. When looking at breeding farms, 24% of them have <50 sows but account for only 2% of the population. On the other hand, only 8% of farms have more than 500 sows but make up for 42% of all breeding sows in Germany. This implies that if a few owners of large farms decide to switch to nVac, a considerable number of sows are affected. However, the decision to switch to nVac might not only be a farmers' own choice. The decision-making process might also be influenced and controlled by a number of external factors (28).

CONCLUSIONS

The analysis performed showed that while vaccination against PRRS was beneficial for all modeled scenarios, vaccinating both sows and piglets proved to be more profitable than vaccinating sows alone. The magnitude of benefits derived from vaccination was more sensitive to changes in vaccine effectiveness than to vaccine price changes. Actual economic benefits of nVac largely depend on the extent to which it would be adopted in the field and consequently also on farmer's attitude toward a new vaccine and willingness to pay.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

HN, JR, BT, and GS-R contributed to the conception and design of the study. BT developed the model and run the analyses. BT and HN evaluated results and discussed their implications. BT wrote a first draft of the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2020.00500/full#supplementary-material

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SYSTEMATIC REVIEW
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Profiling Detection and Classification of Lameness Methods in British Dairy Cattle Research: A Systematic Review and Meta-Analysis

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Lameness is a serious concern in the dairy sector, reflecting its high incidence and impact on animal welfare and productivity. Research has provided figures on its frequency using different methodologies, making it difficult to compare results and hindering farm-level decision-making. The study's objectives were to determine the frequency levels of lameness in British dairy cattle through a meta-analysis approach, and to understand the chronological patterns of how lameness cases are detected and classified in scientific research. A systematic review was conducted using PRISMA-P guidelines for article selection. Random-effects models estimated the pooled frequency measure of lameness with heterogeneity managed through subgroup analysis and meta-regression. Sixty-eight papers were identified, 50 included prevalence and 36 incidence data. The pooled prevalence of lameness in British dairy cattle was estimated at 29.5% (95% CI 26.7–32.4%) whilst all-cause lameness incidence rate indicated 30.9 cases of lameness per 100 cow-years (95% CI 24.5–37.9). The pooled cause-specific lameness incidence rate per 100 cow-years was 66.1 (95% CI 24.1–128.8) for white line disease, 53.2 (95% CI 20.5–101.2) for sole ulcer, 53.6 (95% CI 19.2–105.34) for digital dermatitis, with 51.9 (95% CI 9.3–129.2) attributable to other lameness-related lesions. Heterogeneity levels remained high. Sixty-nine papers contributed to a chronological overview of lameness data source. Although the AHDB Dairy mobility scoring system (MSS) was launched in the UK in 2008 and adopted shortly after by the British Dairy sector as the standard tool for assessing lameness, other methods are used depending on the investigator. Automated lameness detection systems may offer a solution for the subjective nature of MSSs, yet it was utilized in one study only. Despite the recognition of under-reporting of lameness from farm records 22 (31.9%) studies used this data source. The diversity of lameness data collection methods and sources was a key finding. It limits the understanding of lameness burden and the refinement of policy making for lameness. Standardizing case definition and research methods would improve knowledge of and ability to manage lameness. Regardless of the measurement method lameness in British dairy cattle is high.

Keywords: lameness, locomotion, meta-analysis, classification, dairy, cattle, British

INTRODUCTION

Livestock production has changed quite substantially over the last century, in response to supply issues with regards to technological development, and socio-demographic changes with increasing numbers of people and their wealth leading to greater demand for animal products. Extensive subsistence systems have given way to intensive commercial structures (1, 2), which has led to a change in the production environment and consequently to the upsurge and/or increase of the incidence of production diseases, resulting in reduced animal welfare (3–5). The increasing global consciousness regarding animal and food production, and the scientific body of evidence pressures political leaders to debate and legislate animal production toward more environmentally sustainable and higher-welfare standard systems (6).

Lameness is currently one of the main health concerns facing the livestock sector, particularly in the dairy cattle industry. According to the Agriculture and Horticulture Development Board (AHDB) Dairy (formerly known as DairyCo), a UK non-departmental public body funded by farmers and organizations in the food supply chain, it encompasses any foot or leg condition of infectious or non-infectious (environmental and/or farm management factors) etiology leading to abnormal locomotion (7). It has serious implications in terms of animal welfare (8–12) and significant impact in production as a result of reduced milk yield, reproductive performance and weight gain, and increased involuntary culling (13–17). Adding expenditure for the treatment of affected animals to production losses, Willshire and Bell (18) estimated that clinical lameness costs the typical UK dairy herd (defined as 112 Holstein-Friesian cows fed a partial mixed ration, with an average yearly milk yield of 6,885 liters/cow and an average calving index of 410 days) £7,499.30 per year, which translates into 0.97 pence per liter. Previously, Kossaibati and Esslemont (19) estimated the costs of lameness in a British 100-cow herd at £1,715 per year. Bennett and IJpelaar (20) estimated the costs of endemic livestock diseases in the UK, while also providing a score of the welfare impact of those conditions in the animal population. In this exercise lameness cost the UK cattle livestock sector 53.5 million sterling pounds—second to mastitis, the most costly disease—and ranked first in the welfare impact evaluation (20). Additionally the impact of lameness in a cow's mobility and behavior can discourage the adoption of technologies developed for improving the business efficiency such as the Automatic Milking Systems (AMS), which rely on the voluntary attendance of the cow to the milking robot (21, 22). Moreover, being associated with increased lying behavior it is probable that lameness augments the risk of mastitis—the most costly aliment in dairy cattle among production diseases (23).

There is, however inconsistent data on lameness, be it in terms of availability or accessibility (24). This is particularly important when estimating or calculating the frequency of disease; a key parameter for animal health economic analyses. The reliability of the estimates is closely associated with the quality of data available. Farm records are commonly used as source of data for calculating disease frequency, yet studies consistently conclude that lameness in cows is under-reported by farmers (25–27). Whay et al. (28) reported that farmers would underestimate lameness prevalence by 17% when compared with the observations from an independent and trained assessor. Leach et al. (29) reported this difference to be close to 30%, with the mean farmer-reported lameness prevalence at around 7%. Scoring systems with ordinal scales based on animal's posture and walking pattern were developed to aid the detection of lameness. However, the subjectivity inherent in assigning scores and the diversity of scoring instruments used contributes to inconsistencies (30–33). The lack of a standard definition for lameness predisposes misclassification errors (26, 34–36); and the diversity of study designs, and data collection and analysis methodology used in research hampers our ability to compare results across different studies, making it difficult for people involved in the milk value chain to make informed decisions (2, 37). Without a standard method of assessment lameness frequency levels it is hard to understand the trends of the health condition through time and its burden, and to assess the effectiveness of the measures for managing it.

The objectives of this study were to:

- Conduct a meta-analysis to estimate the pooled prevalence and incidence rate of lameness in British dairy cattle since 1823.
- Chronologically analyze the use of different lameness detection and classification methods used in British dairy cattle lameness research, to investigate temporal trends and determine whether specific methods have been used consistently.

MATERIALS AND METHODS

A systematic review to identify papers reporting frequency of lameness in British dairy cattle was conducted in six electronic scientific literature databases—*Agricola*, *Cab Direct*, *Cochrane Library*, *PubMed*, *Scopus,* and *Web of Science* (all databases) on the 4th of January 2020. The systematic review protocol was developed based on the Cochrane guidelines (38), and the PRISMA-P (Preferred Reporting Items for Systematic reviews and Meta-Analyses) statement (39), with specific modifications for a systematic review reporting measures of disease frequency, as recommended by the Joanna Briggs Institute (40). The search was limited to peer reviewed articles, published since 1823 in English. The population search terms were (dairy AND cattle) AND (UK OR Britain OR British OR kingdom). The outcome search terms were (lameness AND (prevalence OR incidence). The following code was used for all six databases considered: (dairy AND (cattle OR cow*) AND (UK OR British OR Britain OR kingdom) AND (lame* OR locomotion) AND (incidence OR prevalence). The search through *Scopus* was limited to abstract, title and keywords. A synthesis of the diagnostic protocols used was also conducted, with the objective of identifying temporal patterns in the use of different methodologies and to determine if any diagnostic protocol has been used consistently over time.

EndNote X9 (Thompson Reuters) bibliographic software was used to manage citations. Duplicate entries were identified, using the automatic function in EndNote and manually during the screening process, by considering the author, the year of publication, the article title, and the volume, issue, and page numbers of the source. In questionable cases, the abstracts or full texts were compared. Conference papers reporting studies that were subsequently published in journals were considered duplicates.

Eligibility Criteria

The systematic review and article selection for the meta-analysis followed the PRISMA guidelines (39) according to the diagram in **Figure 1**.

Titles and abstracts from the records identified in the search were screened for eligibility based on the population, intervention or exposure, comparator group, outcome, study design (PICOS) approach using the following criteria: (i) Population: British dairy cattle; (ii) Outcome: lameness prevalence and/or incidence, lameness causing foot lesions; and (iii) Study design: Randomized controlled trials, cohort studies, case-control studies, cross-sectional studies, case reports and outbreak investigations were all eligible for inclusion if they reported number of dairy cows that were lame (numerator) and the study population (denominator), or if the same could be calculated. Only studies published in peer-reviewed journals were included, with no date restriction. Language of publication was restricted to English. Papers that reported data from previous publications were excluded as to have only one entry per data collection exercise.

If the study met all the inclusion criteria but didn't provide data on the number of lame cows and/or study population the corresponding author was contacted via email in an effort to retrieve the missing information and for clarification. If the corresponding author was not available, one of the co-authors was contacted. If the author(s) did not reply or could not provide the information requested the paper was excluded from the meta-analysis.

In addition to the references identified through the systematic review, five other papers were identified (41–45) following a backward search (also known as chain search) on the papers admitted for full-text screening, and added to the database (**Figure 1**). The backward search involves identifying references cited in an article that may be relevant for the study in question (46).

For the chronological analysis of the use of different lameness detection and classification methods, all studies that underwent full-text screening were considered. Papers with information on the lameness data source were included, regardless of them meeting inclusion criteria regarding lameness data availability. Papers that reported the same original research were considered duplicates and were removed (**Figure 1**). The usage of lameness detection and classification methods through time was analyzed by means of a histogram.

Data Extraction

Data extraction was performed by one reviewer (JSA) and checked for accuracy by MB. Any ambiguities were discussed and consensus reached. The data extracted from the records were based on the recommendations of PRISMA-P (47) and included: (i) study characteristics (authors, year of publication, year or years of data collection, study type—experimental or observational, study design, sample size, sampling strategy); (ii) population data (breed, production system, milking system, grazing regime, housing system, study unit); (iii) outcome data (lameness classification method, lameness assessment frequency, lameness assessment observer, measure of disease frequency); and (iv) numerator and denominator data (number of lame cows, total number of cows in the study population, number of lameness events, population at risk, study duration). The PRISMA-P checklist can be consulted in the **Supplementary Material** section.

Database Management and Parameters

Microsoft Excel (48) was used to create a database with the data extracted from the papers. Most variables contained a substantial number of categories, or range in values. This would result in a high number of strata with small number of papers when conducting the analysis, at the expense of statistical power. In order to solve this problem new binary variables were created based on the values extracted from the papers (**Supplementary Table 2**). Papers reported lameness for different study units depending on their study population: heifers, cows, lactations and culled cows. Papers reporting lameness per lactation were included in the category "cow," assuming that each lactation represents a dairy cow. Sample size was used to create a new binary variable, and to explore the potential effect of smaller sample sizes on lameness estimates. The cut-off for animal sample size was based on the median of the animal sample size for the identified studies. The median was 1,237, the cut-off was defined at 1,230. The choice of the farm number was based on the median of the farm sample size for the identified studies. The median was 4, and the farm sample size cut-off was defined as 5. Given the increasing awareness to the lameness issue through time the years of the start of data collection was used to create five different variables. Different cut-offs were defined: 1995, 2000, 2005, 2008, and 2010. The last 2 years reflect the adoption of the AHDB Dairy mobility scoring system as the dairy industry standard and the implementation of the AHDB Dairy Healthy Feet program, respectively (49). The variables were named *Start of data collection (year)* as to indicate that the cut-off refers to the year data collection was initiated. The five variables were numbered from 1 to 5 with respect to the chronology of the cut-off: 1 would stand for the year 1995 as the cut-off and 5 for the year 2010.

As the incidence rate of lameness was reported in different time units, the incidence data were extracted and standardized for 100 animal-years. To explore the underlying causes of lameness the following grouping of lesions was defined, based on Griffiths et al. (50):

- White Line Diseases (WLD) and Abscess → White Line Disease.
- Sole Ulcer and Sole Hemorrhage/ Bruising → Sole Lesions.
- Bovine Digital Dermatitis and Interdigital Phlegmon/Foul-in-the-foot/Footrot → Infectious-nature lameness.
- All other lesions → Other.

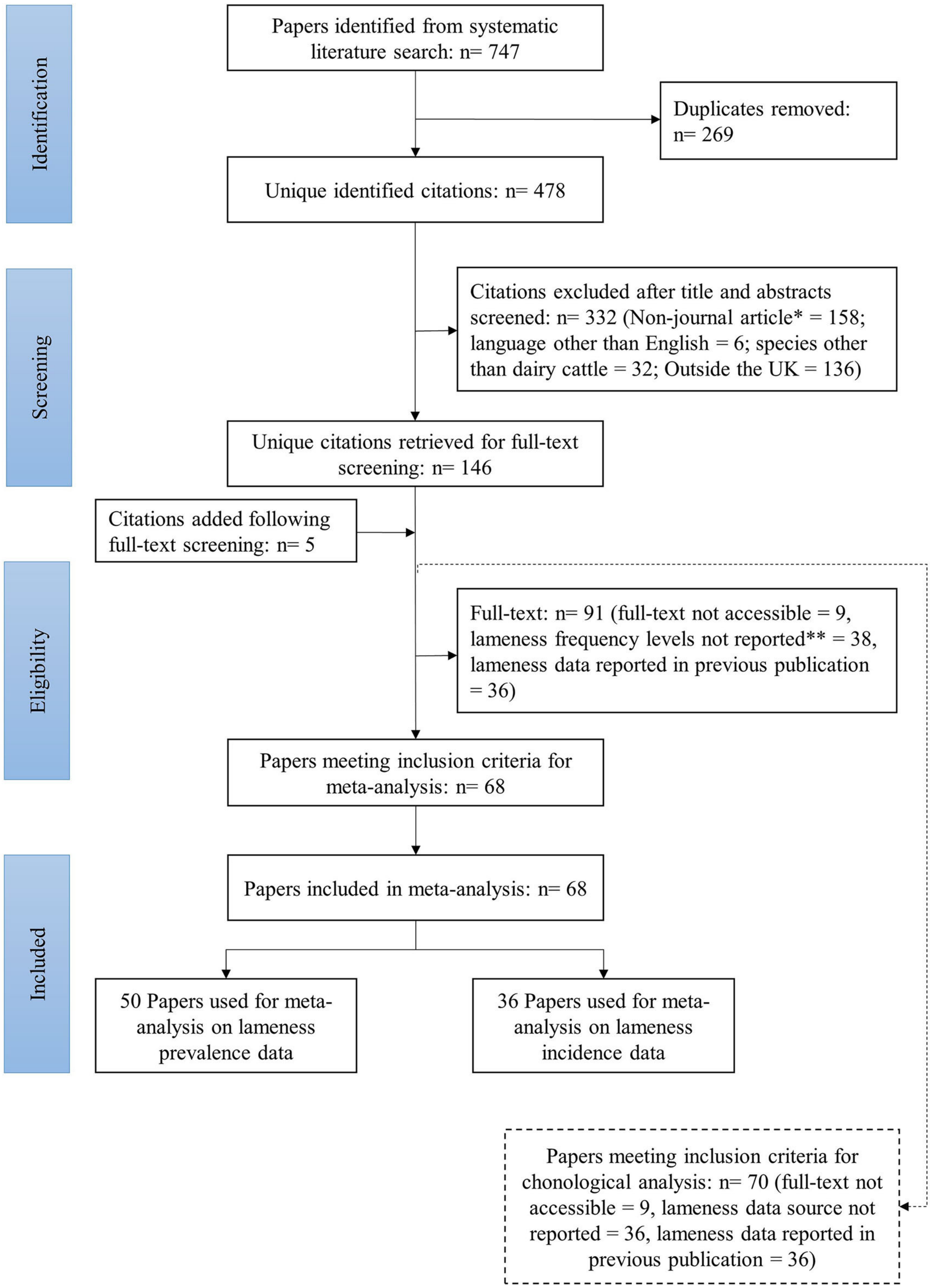

FIGURE 1 | Flow diagram of studies identified by the systematic review and their selection process and inclusion for the meta-analysis on lameness frequency levels in British dairy cattle (*short communications, letters, self-assessments, and review articles were excluded, **if lameness frequency levels were reported but no information on population at risk/denominator was provided/retrievable the paper was excluded).

The identified papers reported lameness based on three distinct study units—cow, heifer and culled cow. Due to the inherent differences of dairy cows in various life stages, and to the fact that reporting disease frequency according to culling reason does not necessarily reflect the herd's disease incidence or prevalence, a pooled-estimate was not considered to be appropriate. Therefore, papers were grouped according to the moment of the production cycle at which lameness frequency was reported, and a meta-analysis conducted on these sub-sets of data.

Methodological Quality Assessment (Risk of Bias)

As advocated by the Cochrane the quality assessment of the studies included in the meta-analysis was focused on the methodological aspects, hence risk of bias (51). The lameness frequency levels reported in the papers included for the meta-analysis were assessed as to their potential risk of bias. This exercise followed the QUADAS2 approach (52) and an adapted tool (see Risk Bias Assessment in **Supplementary Material**) was used to evaluate the potential risk of bias of a set of components and its applicability. The tool was piloted by two researchers (JSA and an invited researcher—BG—who was not otherwise involved in the study) on two randomly selected papers. If there was no agreement between the two researchers when assessing the papers, the tool was revised and re-piloted on two other randomly selected papers. A paper was considered to have a low overall risk of bias if the risk of bias and applicability concerns were low.

Analysis

The primary outcome measure was incidence rate or prevalence of lameness in British dairy cattle. Analysis was conducted using RStudio statistical software (version—1.2.1335; R Foundation for Statistical Computing, Vienna, Austria) using the *meta* and *metafor* packages (53). The *metaprop* function was used to conduct the meta-analysis on the prevalence data and the *metarate* function for the incidence data.

The fixed-effect model disregards the between-study variance and assumes that the methods and underlying population from which the sample was drawn are equal between the different studies. These assumptions did not seem to fit well given the heterogeneity of the methods and sample population between the identified studies. For that reason a random effects model was chosen over a fixed-effect model (54, 55). Data were assessed for skewedness. As it was not normally distributed, data were transformed using arcsine transformation. A sensitivity analysis was conducted comparing the results obtained using the arcsine transformation with those obtained when using other available data transformation methods (56). The GLM model was only used for the prevalence data.

With the exception of the GLM model, all models used the inverse variance method for pooling the estimate of the lameness frequency level. Confidence intervals for individual studies were estimated through the normal approximation interval based on the summary measure (pooled lameness prevalence for studies reporting lameness prevalence and pooled lameness incidence for studies reporting lameness incidence). The DerSimonian-Laird (DL) estimate was used to calculate the between-study variance τ^2 in all models but the GLMM (57, 58). In the latter the Maximum-likelihood estimator was used (59).

Heterogeneity on the Reported Lameness Frequency Levels Between Studies

In the realm of a meta-analysis heterogeneity is defined as the variability of the measure of interest across the selected studies, which can arise from different reasons such as different study methodologies or sampling strategies. Understanding and quantifying heterogeneity is important to allow the researcher to appreciate the range of values the summary measure can take (51). A high heterogeneity level indicates that the variability of the values reported across the individual studies is very large. Studies reporting extreme values that deviate substantially from the summary measure can increase heterogeneity. There could also be a factor or factors, also referred to as moderator(s), by which studies can be grouped that can justify the high levels of heterogeneity (e.g., study design, study type, gender, age of study population). As it may not be adequate to provide a summary measure when heterogeneity levels are high, methods are applied to reduce it (60). A two-step approach was used to address heterogeneity. The first-step was to identify outliers and influential studies. The forest plot was assessed and studies whose 95% confidence intervals did not overlap with that from the pooled estimate were identified. A set of tests followed to formally assess the influence of the outlying effect of individual studies on the pooled estimate by means of the function *influence*. Papers that had a strong influence on the overall estimate were removed from the meta-analysis. The second step was to use a moderator analysis, first by sub-group analysis (univariate), grouping the studies by factors that could explain the heterogeneity, followed by a multiple meta-regression if more than one factor was identified as a predictor of the variance between studies (55). Factors providing a *P*-value of 0.1 or below in the test for moderators were considered moderators and added to the multiple meta-regression model. The model for the multiple meta-regression was developed using the *glmulti* package, and according to the multimodel inference method in which all possible combinations of the identified predictors are explored and parsimony is rewarded (60). The second step was only conducted if there were at least 10 papers, and if there were at least 5 papers per subgroup (60).

Risk factors for lameness were explored in the moderator analysis (breed, grazing regime, calving pattern, housing system, and milking system). Additionally, factors that could have an influence on the reported levels of lameness were also considered in the moderator analysis: lameness data source (records vs. MSS and/or ALDS), study type, study design, study farm(s) location, year of start of data collection and sample size (55).

RESULTS

Chronological Overview of Lameness Classification Methods

Out of the 151 papers that were considered for full-text screening, 70 papers were eligible for the chronological analysis. One paper (61) had been published sometime in the past when compared

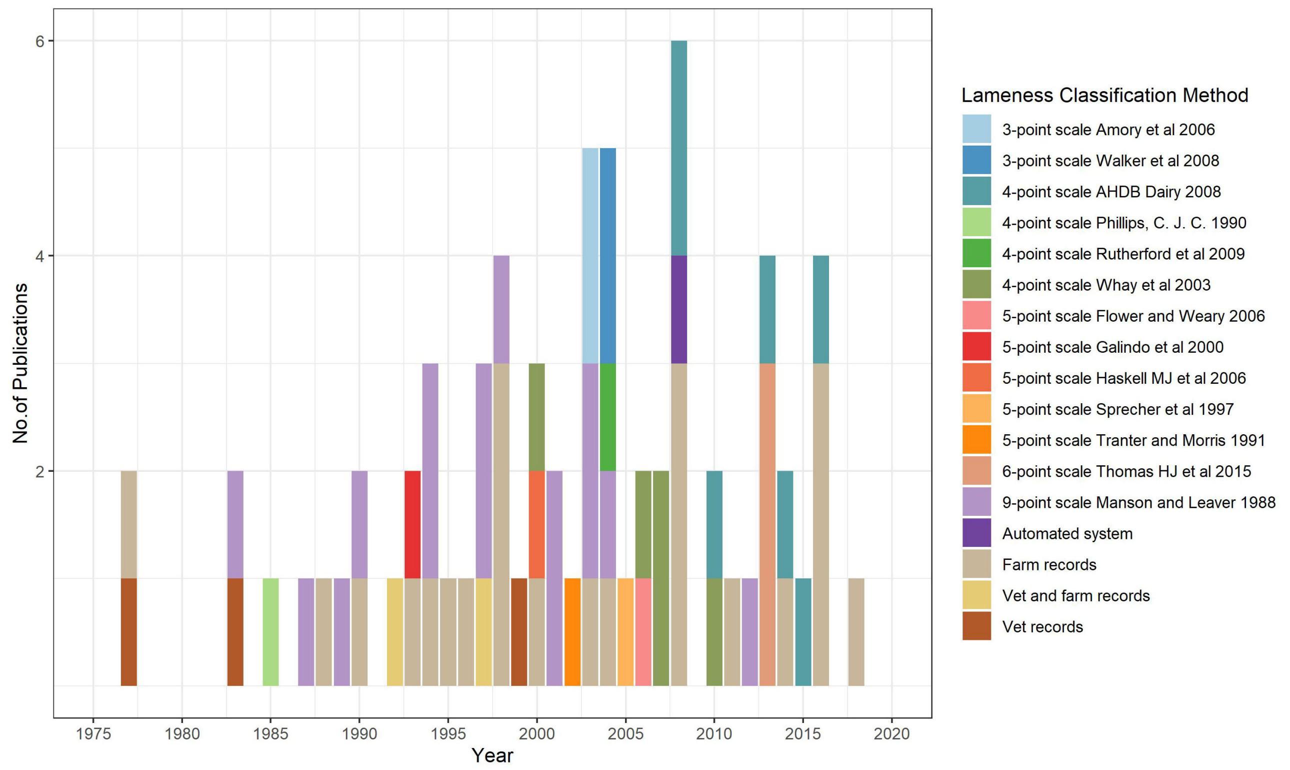

FIGURE 2 | The number of publications in each year, according to the start of the data collection period, and specific lameness detection and classification methods used in research in British dairy cattle since 1975 (each bar represents a paper and the color the method used).

with the other studies and for this reason was excluded from the analysis.

Overall 17 different lameness data sources were identified, among records and mobility scoring systems (MSS). Up until the year 2000 only 3 distinct MSS had been used in lameness research in British dairy cattle. From 2000 onwards another 10 MSS were used in publication regarding the study of lameness in the same population (**Figure 2**). Just over 20% of all the papers used the 9-point scale Manson and Leaver 1988 to collect lameness data, being the most commonly used MSS. The 4-point scale AHDB Dairy 2008 ranked second with about 10% of the papers making use of this MSS. Despite the existence of different mobility scoring tools for assessing lameness in dairy cattle, farm records are still a commonly used lameness data source by research (**Table 1**). Five out of the eight papers making use of data that started being collected from 2014 onwards sourced their lameness data from farm records. Only one paper made use of automated lameness detection systems (ALDS) for collecting data (**Figure 2**).

TABLE 1 | Relative distribution of lameness data sources across the identified papers (*n* = 69) for the chronological overview of lameness classification methods.

Lameness data source	% (*n*)
Farm records	31.9% (22)
9-point scale Manson and Leaver (1988) (62)	21.7% (15)
4-point scale AHDB Dairy (2020) (7)	10.1% (7)
4-point scale Whay et al. (2003) (28)	7.2% (5)
6-point scale Thomas et al. (2016) (63)	4.3% (3)
3-point scale Amory et al. (2006) (31)	4.3% (3)
3-point scale Walker et al. (2008) (64)	2.9% (2)
Vet and farm records	2.9% (2)
Vet records	2.9% (2)
4-point scale Phillips (1990) (65)	1.4% (1)
4-point scale Rutherford et al. (2009) (66)	1.4% (1)
5-point scale Flower and Weary (2006) (67)	1.4% (1)
5-point scale Galindo and Broom (2000) (68)	1.4% (1)
5-point scale Haskell et al. (2006) (69)	1.4% (1)
5-point scale Sprecher et al. (1997) (70)	1.4% (1)
5-point scale Tranter and Morris (1991) (71)	1.4% (1)
Automated system	1.4% (1)

Meta-Analysis on Lameness Frequency Levels

Of the 151 potentially eligible studies, 68 were included in the meta-analysis (**Figure 1**), 16 references were found to have missing data on number of lame animals or population at risk, and author(s) were contacted to see if the information could be provided. Data could not be retrieved on twelve papers—on four papers authors could not be reached, and on eight papers authors weren't able to provide the data. Papers were published from 1946 until 2019, with 75% based on data collected from 1995 onwards (**Table 2**). Fifty had lameness prevalence data whereas 36 had incidence data (**Figure 1**).

The main breed of animals were Holstein, Friesian, or Holstein-Friesian, with about 70% of all studies described the animals as belonging to these breeds (**Table 2**). A significant proportion of studies did not report data on calving pattern, grazing regime, housing system, and milking system. A quarter of the studies were conducted in farms that belonged to research institutes. Most studies were observational (73.5%). In terms of study design 57.4% were longitudinal, and roughly 10.3% of them were cross-sectional. The majority of papers (77.9%) reported on cows, regardless of their age. A small number of papers (10.3%) focused their research on heifers. Two out of every five studies relied on records for their lameness data. More than half of all studies based their research on a sample of <5 farms and/or 1,230 animals (65.6%) (**Table 2**).

Sections Meta-Analysis on Lameness Prevalence Levels and Meta-Analysis on Lameness Incidence Rate Levels will concentrate on the results from the papers reporting lameness prevalence and incidence rate at cow level.

Meta-Analysis on Lameness Prevalence Levels

Fifty studies were included in the meta-analysis on lameness prevalence data. Forty-two, five and three studies reported lameness prevalence at cow, heifer and culled cow level, respectively (**Supplementary Table 4**). The results presented in this section are based on the 42 papers reporting lameness prevalence at cow level. Pooled estimates are provided along with their 95% confidence intervals (CI). The 95% prediction intervals (PI) are also provided except for the sub-group analysis results.

Two outliers were identified. The overall pooled estimate for the prevalence in British dairy cattle after the removal of the outliers was 29.5% (95% CI 26.7–32.4% and 95% PI 13.8–48.2%). Heterogeneity was present and extensive (**Table 3** and **Figure 3**).

The pooled estimates between subgroups when papers were grouped per variables *Start of data collection (year) 1*, *Start of data collection (year) 2, Start of data collection (year) 3, Start of data collection (year) 4,* and *Start of data collection (year) 5* were statistically different (p-value for the test of moderator < 0.1) and therefore were considered as moderators for the meta-regression (**Table 4**). As there were <5 papers in one of the categories for variable *Milking System* no sub-group analysis was conducted on this factor.

The five identified predictors were used in the multiple meta-regression model. The model with the moderator *Start of data collection (year) 2* (year 2000 as cut-off) was the most parsimonious model. The pooled estimate for papers published from 2000 onwards was 34.9% (95% CI 30.1–39.9%), roughly 15% more when compared with the pooled estimate from studies published before the year 2000 (20.0%; 95% CI 16.3–24.0%) (**Figure 4**).

Meta-Analysis on Lameness Incidence Rate Levels

Lameness incidence rate data was extracted from thirty-six studies, thirty-one of which reported the measure at cow level.

TABLE 2 | Summary statistics of the final set of studies reporting lameness frequency levels in British dairy cattle (n = 68).

Variable	Category	% of papers (n)
Start of data collection (year) 1	Before 1995	23.5% (16)
	1995 and onwards	76.5% (52)
Start of data collection (year) 2	Before 2000	38.2% (26)
	2000 and onwards	61.8% (42)
Start of data collection (year) 3	Before 2005	58.8% (40)
	2005 and onwards	41.2% (28)
Start of data collection (year) 4	Before 2008	66.2% (45)
	2008 and onwards	33.8% (23)
Start of data collection (year) 5	Before 2010	76.5% (52)
	2010 and onwards	23.5% (16)
Breed	Holstein/Friesian/Holstein-Friesian	67.6% (46)
	Other 4	20.6% (14)
	Not reported	11.8% (8)
Calving pattern	Year-round	23.6% (16)
	Other	27.9% (19)
	Not reported	48.5% (33)
Grazing regime	Grazing	35.3% (24)
	Other	30.9% (21)
	Not reported	33.8% (23)
Housing system	Cubicle	48.5% (33)
	Other	22.1% (15)
	Not reported	29.4% (20)
Milking system	Conventional	57.4% (39)
	Other	2.9% (2)
	Not reported	39.7% (27)
Study farm(s) belonging to research institute	Yes	23.5% (16)
	No	76.5% (52)
Study Type	Experimental	26.5% (18)
	Observational	73.5% (50)
Study design	Cross-sectional	10.3% (7)
	Longitudinal	57.4% (39)
	Negatively controlled RCT	2.9% (2)
	Positively controlled RCT	1.5% (1)
	Retrospective longitudinal	27.9% (19)
Study unit	Cow	77.9% (53)
	Culled cow	5.9% (4)
	Heifer	10.3% (7)
	Lactation	5.9% (4)
Lameness data source	Mobility scoring system	57.3% (39)
	Records	41.2% (28)
	Other	1.5% (1)
Sample size a	Less than 1,230 animals	52.9% (36)
	1,230 animals or more	47.1% (32)
Sample size b	Less than 5 farms and/or 1,230 animals	63.2% (43)
	At least 5 farms and 1,230 animals	36.8% (25)

TABLE 3 | Summary of the results from the meta-analysis of studies reporting lameness prevalence at cow level using arcsine data transformation method.

No of studies	Pooled prevalence	95% CI	95% PI	Heterogeneity measures			
				Cochran's Q	*P*-value Q	Tau^2	I^2(%)
Before outlier identification and removal							
42	0.299	0.261–0.339	0.087–0.572	34975	<0.001	0.019	99.9
After outlier identification and removal							
40	0.295	0.267–0.324	0.138–0.482	12892	<0.001	0.009	99.7

One paper reported incidence per culled cow whereas the remaining four reported at heifer level (**Supplementary Table 5**). Additionally, data on the underlying cause of lameness were extracted from papers that reported it and a meta-analysis conducted. The results presented are based on incidence rate data from papers reporting cases at the cow level.

Two studies were identified as outliers and removed from the analysis. After the removal of the outliers the overall pooled estimate for all-causes incidence rate in British dairy cattle was 36.8 cases per 100 cow-years (95% CI 29.3–45.3 and 95% PI 5.6–95.5). Heterogeneity was present and extensive (**Table 5** and **Figure 5**).

Few studies provided information on the lameness underlying cause, ranging from 11 (*Sole Ulcer, Sole Hemorrhage/Bruising* category) to 8 (*White Line Disease, White Line Disease and Abscess, Bovine Digital Dermatitis,* and *Other lesions* categories). The pooled incidence rate per 100 cow-years was 66.1 (95% CI 24.1–128.8), 53.2 (95% CI 20.5–101.2), 53.6 (95% CI 19.2–105.34), and 51.9 (95% CI 9.3–129.2) for *White Line Disease*, *Sole Ulcer*, *Bovine Digital Dermatitis,* and *Other lesions,* respectively. As with the meta-analysis on the all-causes incidence rate data, the heterogeneity was present and high for all lameness-related lesions (**Table 6**).

To deal with the high heterogeneity left after the removal of outliers a sub-group analysis was conducted. As with the meta-analysis on prevalence data no sub-group analysis was conducted on the variable *Milking System*.

Breed, Study Type, Housing Regime, *Grazing Regime*, *Sample Size a,* and *Sample Size b* were identified as predictors for heterogeneity among reported incidence across the different studies with statistical significance (**Table 7**).

The six identified predictors were used in the multiple meta-regression model. The most parsimonious model was the one with the moderator *Sample Size a*. The pooled incidence rate of lameness per 100 cow-years for papers based on a sample of 1,230 animals or more was 24.5 (95% CI 17.1–33.3), less than half of the when compared with the pooled estimate from studies based on a sample of <1,230 animals (60.2; 95% CI 38.3–86.9) (**Table 7** and **Figure 6**).

Risk of Bias

The results of the assessment are presented in **Supplementary Table 3** and **Supplementary Figure 1** in the Risk Bias Assessment section of the Supplementary Material. Overall all papers were classified at high risk of bias. Even studies that were addressing the review question had sample populations resulting from convenience sampling with high concerns for its effect on the estimate of lameness frequency. The selection of subset of animals within the sample population (e.g., heifers or milking cows) and lameness data source were additional concerns to the introduction of bias (farm records have a recognized issue of under-reporting, and mobility scoring system are subjective by nature).

Sensitivity Analysis on the Different Data Transformation Methods

Tables with the findings of the sensitivity analysis are provided in **Supplementary Tables 6**, **7**. Below a summary of the main results is presented.

Prevalence Data Analysis

The maximum variation in the pooled prevalence when comparing the results between the different models was of about 6% (from 29.9% in with arcsine and double arcsine transformations to 28.1% in the GLM model). The most significant difference was when the lower limits of the 95% prediction intervals were compared: the figure was nearly twice as high with logit transformation (9.9%) when compared with the GLM method (4.9%). Outliers were identified in methods except for the GLM. The most significant difference was in the logit transformation method where the removal of the outliers led to an increase of roughly 3% in the pooled estimate. Heterogeneity was extensive regardless of the method used (**Supplementary Table 6**).

Incidence Data Analysis

Before the removal of outliers the arcsine and double arcsine methods performed quite similarly, and had about 20% more cases per 100 cow-years when compared with the logit transformation. The removal of the outliers translated into a reduction of roughly 8 cases per 100 cow-years in the arcsine and double arcsine methods, and an increase of about 3 cases per 100 cow-years in the logit transformation. After the removal of the identified outliers all three transformation method provided very similar results, with a maximum of 4% variation when comparing the arcsine with the logit method. Heterogeneity was present and extensive irrespective of the data transformation method used (**Supplementary Table 7**).

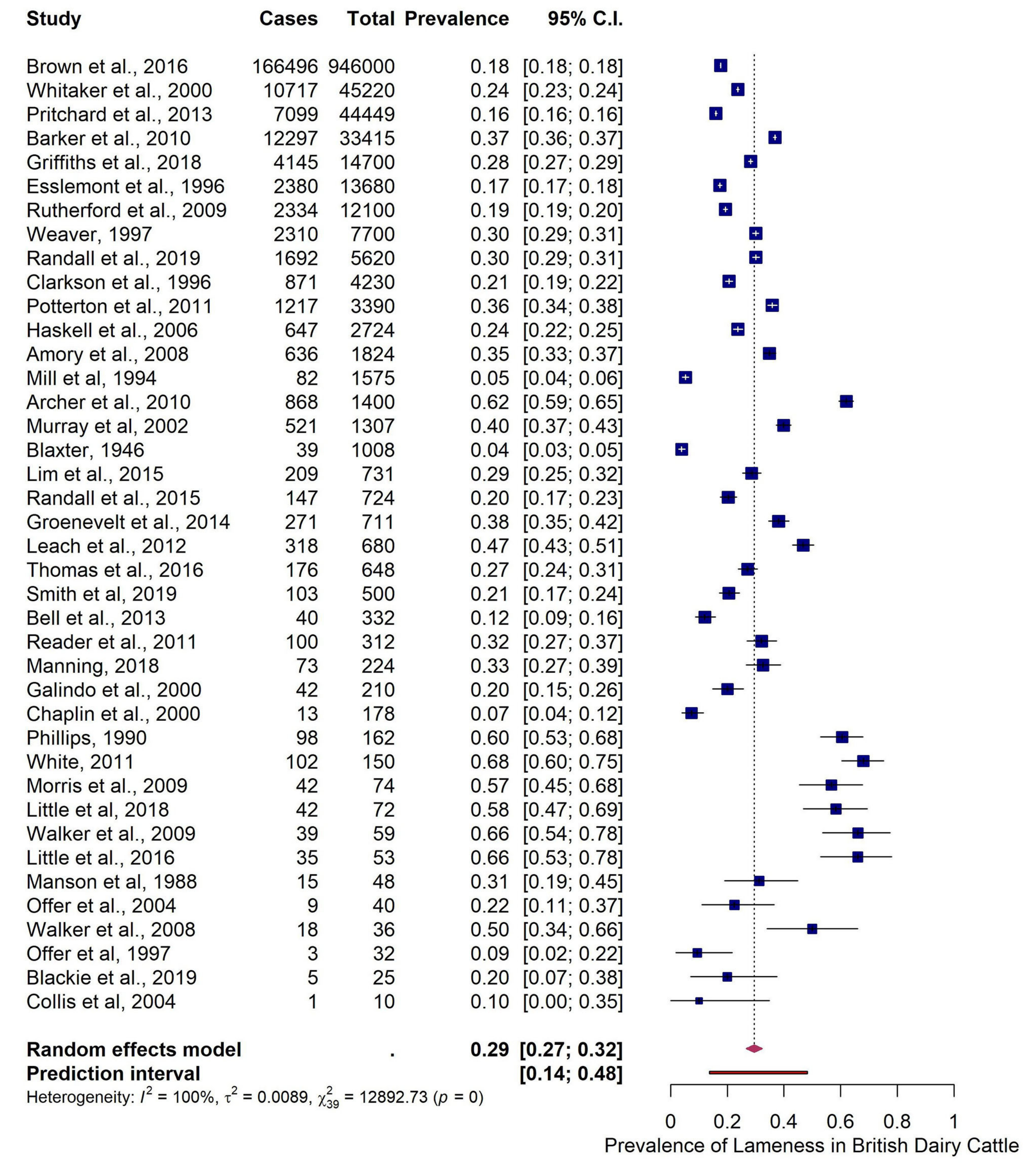

FIGURE 3 | Meta-analysis on reported lameness prevalence in British dairy cattle from identified studies.

DISCUSSION

The usefulness of outputs from meta-analysis in economic evaluations has been highlighted previously (72, 73). The study performed aimed to generate prevalence and incidence parameters to make assessments of the burden of lameness in British dairy cattle, and to provide a chronological overview of the different lameness detection and classification method

TABLE 4 | Sub-group analysis (univariate analysis) for the papers reporting lameness prevalence at cow level.

Moderator	Subgroup	No of studies per subgroup	Pooled prevalence per subgroup	95% CI	*P*-value for QM	Residual heterogeneity (H)	Residual heterogeneity (I^2) (%)
Lameness data source	Mobility scoring system	27	0.294	0.253–0.337	0.672	13.04	99.4
	Records	13	0.283	0.251–0.315			
Study type	Observational	29	0.279	0.249–0.311	0.263	18.11	99.7
	Experimental	11	0.338	0.241–0.443			
Study farm(s) location	Not at Research Institute	32	0.289	0.258–0.320	0.667	18.39	99.7
	At Research Institute	8	0.325	0.173–0.499			
Study design	Cross-sectional	7	0.246	0.182–0.316	0.127	13.86	99.5
	Other	33	0.304	0.278–0.329			
Breed	Holstein[a]	26	0.279	0.255–0.305	0.976	13.40	99.4
	Other	9	0.278	0.214–0.348			
Grazing regime	Other	12	0.308	0.268–0.349	0.578	9.2	99.0
	Grazing	16	0.333	0.256–0.415			
Housing system	Multiple	9	0.293	0.233–0.357	0.189	12.56	99.4
	Cubicle	20	0.357	0.285–0.433			
Calving pattern	Other	11	0.371	0.324–0.420	0.697	8.23	98.5
	Year-round	8	0.334	0.171–0.521			
Start of data collection (year) 1	1995 and onwards	33	0.319	0.287–0.353	0.004*	18.36	99.7
	Before 1995	7	0.195	0.128–0.273			
Start of data collection (year) 2	2000 and onwards	27	0.349	0.301–0.399	<0.001*	18.33	99.7
	Before 2000	13	0.200	0.163–0.240			
Start of data collection (year) 3	2005 and onwards	19	0.368	0.305–0.433	<0.001*	18.28	99.7
	Before 2005	21	0.231	0.199–0.263			
Start of data collection (year) 4	2008 and onwards	14	0.368	0.302–0.436	0.005*	16.37	99.6
	Before 2008	26	0.258	0.219–0.298			
Start of data collection (year) 5	2010 and onwards	11	0.356	0.297–0.418	0.023*	16.02	99.6
	Before 2010	29	0.273	0.234–0.313			
Sample Size a	1,230 animals or more	17	0.263	0.225–0.302	0.169	18.26	99.7
	less than 1,230 animals)	23	0.328	0.245–0.417			
Sample Size b	More than 5 farms and 1,230 animals	14	0.265	0.218–0.314	0.171	15.20	99.6
	less than 5 farms and/or 1,230 animals	26	0.319	0.259–0.380			

[a]*Herds which cows were mainly Holstein, Friesian and/or Holstein-Friesian.* ***Variables considered as moderators.*

and data sources. The analysis indicates that there are problems with how this health condition is reported and measured. It is particularly concerning that 4 out of the 6 studies identified in the SLR published from 2015 onwards based their findings in farm records, a data source highlighted for under-reporting lameness levels (25–28). Additionally the diversity in mobility scoring methods, their intrinsic subjective nature and the potential lack of correspondence adds uncertainty to how consistently is lameness being measured between studies. Other authors have raised this problem (2, 30, 34, 35, 37, 74, 75), there is a need for greater standardization in lameness data collection methods and case definition. This would allow for a more accurate understanding of lameness trends through time and inform the interested parties as to the effectiveness of the adopted approaches for tackling the problem. Despite these problems the analysis has provided great insight into the scientific documentation of lameness and its potential limitations in the estimates of the economic burden of this problem and its serious implication in animal welfare.

We decided to group papers according to the study unit at which lameness was reported, and to concentrate the analysis and report results on cows rather than heifers and culled cows. Heifers are known to have lower incidence of lameness than older cows (76). Additionally culling records are not a good indicator of lameness frequency in dairy cattle, reporting low levels of the ailment (16, 77) when compared with evaluations from independent observers (28, 50). Pooling lameness levels from papers reporting it at heifer and culled cow level with those reporting it at cow level would probably underestimate our results.

The most parsimonious model for the analysis of prevalence data had *Start of data collection (year) 2* as the only moderator. The pooled prevalence for studies for which data began being collected before the year 2000 was 20.0% (95% CI 16.3–24.0%). This is in line with what Clarkson reported (20.6%) in 1996 (78). The two most recent lameness prevalence studies in British dairy cattle reported higher levels of lameness. Griffiths et al. (50) using data collected in 2015 and 2016 estimated a 28.2% prevalence, whereas Randall et al. (79) using data collected in 2014 30.1%. These most current estimates of lameness prevalence in British dairy cattle are similar (although slightly lower) to the pooled estimate for studies for which data began being collected in 2000 and onwards 34.9% (95% CI 30.1–39.9%). It could be that awareness regarding lameness has increased over the years. The fact that the *Start of data collection (year) 4* (year 2008 as cut-off) and *Start of data collection (year) 5* (year 2010 as cut-off) were identified as predictors for the variance in the reported estimates between studies could reflect a higher consciousness to the problem as it was when the British dairy sector adopted the AHDB 4-point MSS as a standard tool in lameness assessment and when the *Healthy Feet* program was launched—two marks in the history of lameness management in the UK (49). Regardless of the potential increase of awareness to the lameness problem in dairy cattle and/or ability to measure it accurately, the frequency levels of this health condition have remained substantially high across time. It is important to acknowledge that the intensification of production system have created pressure on the animal's productivity, sometimes at the expense of their health (4). The selection of animals based solely on milk production has also led to the increase of the incidence of different diseases, namely lameness (80). Lameness has been associated with milk yield: animals with higher milk yields are at higher risk of developing the ailment (81). Yet, early identification of lameness cases and prompt action has proven to be effective in reducing the impact of lameness and maintaining its levels low (82, 83). Developing tools to identify lameness in pre-clinical stages would allow for early intervention providing the necessary support for preventing animals from becoming obviously lame. Genetic improvement of herds based not just on production traits such as milk yield and fertility, but also on resistance to certain health condition such as lameness could offer a way to reduce the incidence of the ailment (84–86). Apart from all the different strategies that can be adopted to alleviate lameness frequency and/or its impact it must be acknowledged that it is up for farmer to make the decisions and take action in managing the health and welfare of the animals. It is thus important to understand the perceptions and motivations of farmers if measures are to be effectively implemented (38, 87).

The moderator *Sample Size a* (1,230 cut-off) retrieved the most parsimonious model when analyzing the lameness incidence data set. The estimated pooled incidence for the studies with more than 1,230 animals indicated 24.5 cases of lameness per 100 cow-years (95% CI 17.1–33.3). This is in line with what Esslemont and Kossaibati (88) and Whitaker et al. (89) estimated—24.5 and 21.8, respectively—but considerably lower than what Clarkson et al. (78) estimated—54.6 cases per 100 cow-years. It must be noted that most studies with a sample size of more than 1,230 animals (12 out of 17) were based on farm records, a data source prone to under-reporting (28, 29). On the other hand 2 out of every 3 studies with a sample size of less 1,230 animals relied on mobility scoring methods to assess lameness. Part of the observed difference could result from the different methods that were used for collecting lameness data. The pooled estimate for incidence rate for studies with <1,230 animals was 60.2 cases of lameness per 100 cow-years (95% CI 38.3–86.9), which is close to what Clarkson et al. (78) estimated. The figure for the incidence in the later study was based on farm records. However, it must be noted that the enrolled farms had regular visits from researchers who mobility scored the herd for the duration of the study, which could have had an effect on the accuracy of the records kept by the farmer.

The impact of lameness is cause-specific, resulting from different adverse effects in the animal's production capacity, and different treatments and prevention and control strategies (17). Identifying the underlying disease leading to lameness is valuable information for the management of hoof problem(s) and for conducting economic studies on this health condition. However, few studies were found to report lameness data with this level of granularity. The fact that collecting such data can be quite time consuming and labor intensive could offer an explanation for this. Dairy farming is time and labor demanding and farmers will have priorities other than to diagnose and register the lameness-causing lesion. Hoof trimmers are an eventual good data source but the pressure to deal with all the animals in a timely manner can lead to misclassification errors and no reporting of such data. In addition to the lack of available data, the diversity in methodologies and sample sizes, and high variance in the reported incidence rate between studies resulted in very wide 95% CI for the pooled estimate.

Data availability and accessibility are bottle-necks when studying animal diseases and their impact (24). The fact that lameness is a symptom rather than a disease in itself (with a diversity of diseases that can cause the ailment), and that different methods are used to capture lameness information, makes data consistency an even higher challenge when studying this health condition (34, 35). Three main findings were drawn from the chronological analysis of lameness detection and classification

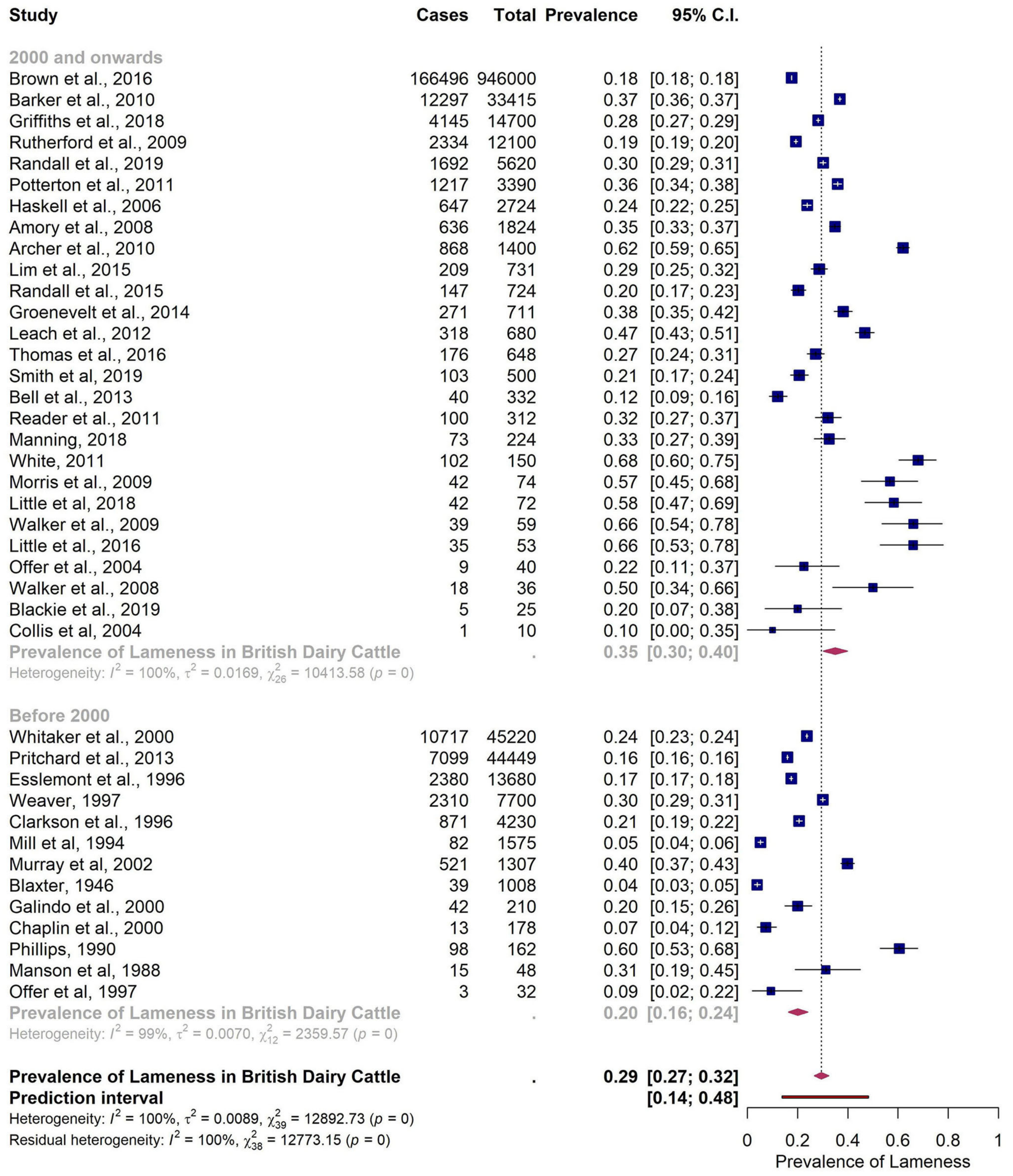

FIGURE 4 | Subgroup analysis of reported prevalence of lameness in British dairy cattle at cow level with Start of data collection (year) 2 as a moderator (year 2000 as cut-off).

TABLE 5 | Summary of the results from the meta-analysis of studies reporting lameness incidence rate (100 cow-years) at cow level using the arcsine data transformation method, before and after outlier removal.

No of studies	Pooled Incidence rate (100 cow-years)	95% CI	95% PI	Heterogeneity measures			
				Cochran's Q	*P*-value Q	Tau^2	I^2(%)
Before outlier identification and removal							
31	45.2	36.9–54.3	8.8–109.7	112985	<0.001	0.033	100.0
After outlier identification and removal							
29	36.8	29.3–45.2	5.6–95.5	109127	<0.001	0.032	100.0

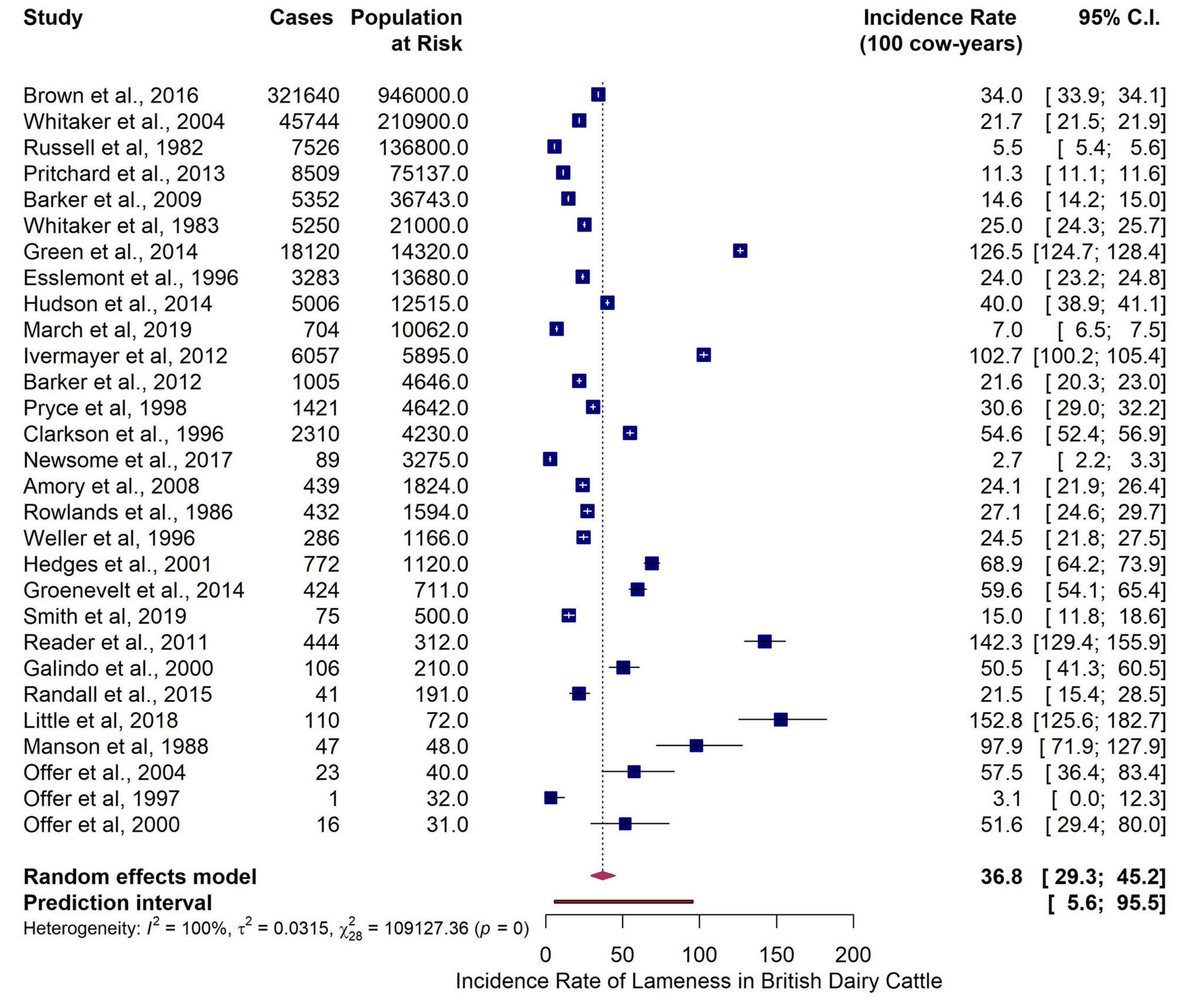

FIGURE 5 | Meta-analysis on reported lameness incidence rate (100 cow-years) in British dairy cattle from identified studies after outlier removal.

TABLE 6 | Summary of the results from the meta-analysis of studies reporting lameness causing lesions incidence rate (100 cow-years) at cow level using the arcsine data transformation method, after outlier removal.

Lesion(s)	No of studies (No of outliers)	Pooled incidence rate (100 cow-years)	95% CI	95% PI	Heterogeneity measures			
					Cochran's Q	*P*-value Q	tau 2	I^2 (%)
Wld[a]	7 (1)	66.1	24.1–128.8	14.4–402.4	23947	<0.001	0.188	100.0
Wldabs[b]	6 (2)	75.2	25.5–151.2	24.0–494.8	23881	<0.001	0.205	100.0
Su[c]	9 (1)	53.2	20.5–101.2	10.5–317.9	26148	<0.001	0.179	100.0
Sushb[d]	10 (1)	46.6	22.2–79.8	1.9–226.3	44594	<0.001	0.115	100.0
Bdd[e]	8 (1)	53.6	19.2–105.3	13.6–335.9	26129	<0.001	0.179	100.0
Bddfr[f]	7 (2)	60.2	26.6–107.5	3.6–303.2	43872	<0.001	0.123	100.0
Other[g]	7 (1)	51.9	9.3–129.2	67.6–512.3	43199	<0.001	0.315	100.0

[a]White Line Disease, [b]White Line Disease and Abscess, [c]Sole Ulcer, [d]Sole Ulcer, Sole Haemorrhage/Bruising, [e]Bovine Digital Dermatitis, [f]Bovine Digital Dermatitis and Interdigital Phlegmon (foot rot), [g]Other hoof related lesions.

system: the mobility scoring system (MSS) adopted in 2008 by the industry as the standard (the AHDB Dairy mobility scoring system) is not the only MSS being used for assessing lameness in dairy cattle; the diversity of MSS used and the fact that these are subjective in nature and prone to observer bias makes it more difficult to aim for consistency; and farm records are still a source of data when studying lameness despite the under-reporting problems identified in research (28, 29). The mobility scoring systems are based on ordinal scales, and depend on the observer's experience to detect changes in the animal's locomotion that fit the descriptors for each level in the scale. The scales of the identified MSS ranged from 9 to 4 points with different descriptors. To make the assessments between studies comparable the ordinal scales are translated into binary (lame vs. non-lame) or shorter scales (non-lame, mildly lame, and severely lame). Since the descriptors are not identical between scoring system this could bring about issues of consistency and hamper comparison. Regardless of the myriad of MSS available, further investigation is required to study the impact of the use of different MSS in the reported lameness levels, and to explore how related MSS are between each other. Although technology for the detection of lameness based in artificial intelligence is available only one study has made use of data collected by an automated lameness detection system (ALDS). It must be noted that the validation of ALDS is achieved by comparing the results obtained with the current reference standard—direct observation of the animal. Once parameterized the tool can offer a way to avoid some biases associated with the subjective nature of assessing lameness through direct observation of the animal's behavior and locomotion. However, if the sensitivity was parameterised according to the best available method—MSS—then it is likely that the results from automated system will be influenced by the standard that provided the threshold for lameness condition. Another limitation to ALDS is that some hoof lesions will not alter the animal's behavior or locomotion. This is particularly significant for Bovine Digital Dermatitis, an important infectious hoof disease (75). Although ALDS are a promising tool for objectively identifying lameness there is need for further research in order for it to become a reality. The use of MSS was associated with the study farm(s) location. Research institutes will have implemented a particular system in their routine welfare assessment and thus studies that have made use of their data set for conducting analysis will report this MSS. This could lead to incorrectly concluding that the AHDB system has not been widely adopted if many papers make use of the data set from these dairy farms belonging to research institutes. Nevertheless, and as previously mentioned, diversity in the methods by which lameness is classified brings about inconsistency and hampers comparability. The discussion about the need for University-Industry engagement offer an opportunity to reflect on how to harmonize the tools and communication used by both sectors with respect to lameness in dairy cattle.

The data extracted from the papers was skewed and so it was transformed through the arcsine method to improve its statistical properties. The double arcsine method has been advocated by researchers as the model of choice for conducting meta-analysis with binomial data (53, 55, 90). However, Schwarzer et al. (56) has highlighted potential misleading results from back-transformed data when this method is used, especially when sample size is small. Following Schwarzer et al. (56) recommendations a sensitivity analysis was done to assess the effect of the different data transformation methods on the results. This analysis indicated minor differences in the pooled estimates when using the different methods. The logit transformation was the method that showed most significant differences. Research has indicated this approach to be problematic when analyzing binomial data, placing undue weight on studies reporting extreme proportions and failing to stabilize variance in studies with smaller sample sizes (53, 56, 90). In sum, the arcsine transformation seemed to be the most suitable option.

The choice of a random-effects model seemed appropriate considering the heterogeneity of the methods and sample population between the identified studies, and given the need

TABLE 7 | Sub-group analysis with the papers reporting lameness incidence rate (100 cow-years) at cow level after outlier removal.

Moderator	Subgroup	No of studies per subgroup	Pooled incidence rate (100 cow-years) per subgroup	95% CI	*P*-value for QM	Residual heterogeneity (H)	Residual heterogeneity (I^2) (%)
Lameness data source	Mobility scoring system	13	36.9	24.2–52.4	0.989	62.93	100.0
	Records	16	36.8	26.9–48.4			
Study Type	Observational	22	30.7	23.1–39.5	<0.001*	63.37	100.0
	Experimental	7	63.4	45.4–84.4			
Study Farm(s) Location	Not at Research Institute	22	33.9	25.8–43.1	0.309	63.57	100.0
	At Research Institute	7	48.3	24.1–80.9			
Breed	Holstein[a]	20	45.7	34.7–58.2	0.0020*	45.83	100.0
	Other	6	19.4	9.8–32.4			
Grazing regime	Grazing	13	64.6	43.6–90.1	<0.001*	19.66	99.7
	Other	5	17.5	12.2–23.9			
Housing System	Multiple	6	14.8	7.5–24.6	0.03*	43.14	99.9
	Cubicle	12	54.2	19.2–106.9			
Calving Pattern	Year-round	5	52.4	18.2–104.2	0.577	43.14	99.9
	Other	9	39.5	22.4–61.3			
Start of data collection (year) 1	1995 and onwards	19	38.1	29.8–47.5	0.694	51.55	100.0
	Before 1995	10	34.6	21.2–51.3			
Start of data collection (year) 2	2000 and onwards	14	43.7	28.5–62.1	0.164	47.84	100.0
	Before 2000	15	31.0	23.3–39.8			
Start of data collection (year) 3	2005 and onwards	9	55.8	28.9–91.5	0.066	45.37	100.0
	Before 2005	20	29.3	23.6–35.6			
Start of data collection (year) 4	2008 and onwards	8	47.8	22.1–83.4	0.316	45.51	100.0
	Before 2008	21	32.9	26.5–40.1			
Start of data collection (year) 5	2010 and onwards	6	31.6	13.7–56.8	0.583	52.07	100.0
	Before 2010	23	38.5	28.9–49.5			
Sample Size a	1,230 animals or more	17	24.5	17.1–33.3	0.0019*	62.00	100.0
	less than 1,230 animals	12	60.2	38.3–86.9			
Sample Size b	More than 5 farms and 1230 animals	11	20.7	14.3–28.2	0.0021*	43.29	99.9
	less than 5 farms and/or 1,230 animals	18	49.7	31.9–71.6			

[a]Herds which cows were mainly Holstein, Friesian and/or Holstein-Friesian. ***** *Variables considered as moderators.*

to consider both the intra and inter-study variance of lameness frequency (54, 55).

With the exception of the GLM model, the DerSimonian and Laird (DL) method was used to estimate the between study variance. Other authors argue that the restricted maximum likelihood (REML) is the approach of choice, despite of higher computational complexity (59). However, it seems that the difference observed when comparing results from these two methods is generally insignificant and its impact negligible (91).

Heterogeneity in the outcome of interest between studies is critical aspect of conducting a meta-analysis (90) and one of its main objectives was to reduce it as much as possible (92). The identified studies were quite diverse in terms of study design, data collection method and analytical approach. This diversity is hard to manage when the number of papers is not big enough to perform the analysis aimed at dealing with heterogeneity. This was particularly marked when exploring the moderator effect of certain factors such as *Grazing Regime, Housing System,* and *Milking System*, for which only a small number of studies had data on. Despite having identified moderators that explained part of the observed heterogeneity, it remained high and unexplained—a common finding when conducting this sort of analysis in

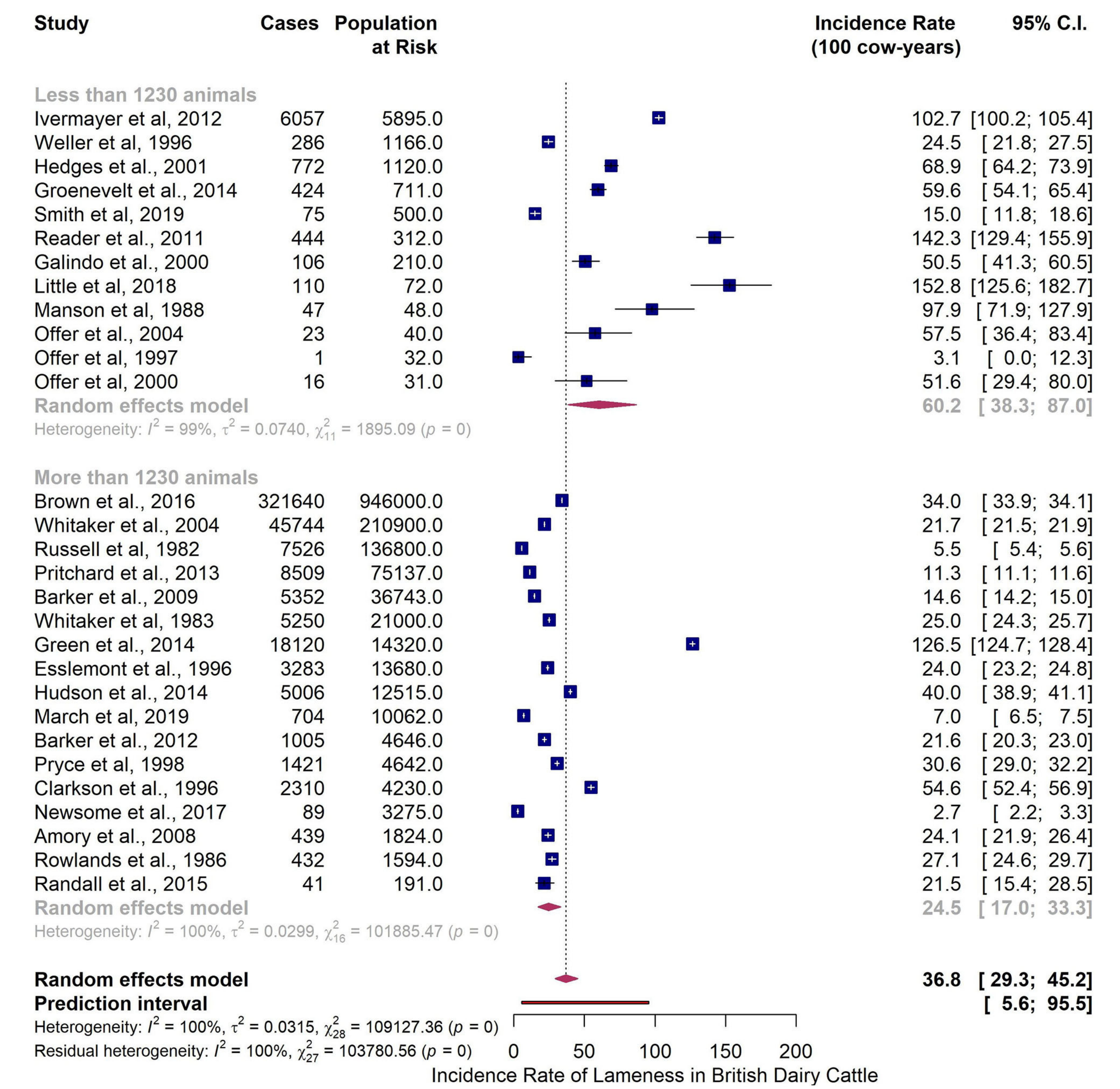

FIGURE 6 | Subgroup analysis of reported incidence rate of lameness in British dairy cattle at cow level with Sample Size a as a moderator.

disease frequency data (93). As a result of the high residual heterogeneity the interpretation of results should be taken with caution as it may not be appropriate to summarize the data into a single estimate. However, having described the predictors for such heterogeneity is a valuable output from the analysis as these could indicate risk factors for lameness. The estimated prediction intervals are also an important output. While taking into account the variability of individual studies, they are wider than the 95% CI and provide the range of values that would capture 95% of the estimates of lameness frequency levels—meaning that if we were to pick a study on the frequency of lameness in British dairy cattle the figure we would get would fall within that range 95% of the times. These parameters can then be used to inform economic analysis by means of a sensitivity analysis with worst and best case scenarios.

When conducting the meta-analysis on incidence data *Housing Regime* was a factor that seemed to explain part of the observed heterogeneity between studies. These findings are in accordance with conclusions reported in previous publications. Housing system also plays a role in the epidemiology of lameness, with straw yards having a protective effect on lameness incidence (66). The variable *Grazing Regime* was also identified as predictor for the variance of the estimate between studies. As opposed to what research has highlighted (69) grazing systems had a higher incidence rate of lameness (47.5 cases per 100 cow-years; 95% CI 28.8–70.8) when compared with the studies that reported lameness based on a sample that included also included non-grazing systems (17.5 cases per 100 cow-years; 95% CI 12.2–23.9). With the well-documented under-reporting problem of lameness in farm records there was some expectation as to the variable *Lameness Data Source* being identified as a predictor. However, the pooled estimate of the papers with lameness record-base data was not statistically significantly different from the pooled estimate of the papers with lameness data collected through MSS and/or ALDS.

The authors acknowledge that the search terms used in the systematic literature review were somewhat narrow and that some references focusing on lameness in British dairy cattle might have been missed with the search strategy. Yet considering the research question the search terms seem to be adequate when identifying publications focused on reporting lameness frequency levels in British dairy cattle. Limiting the search to research conducted in British dairy cattle was strategic as the results from this analysis are intended to be used in an economic assessment of lameness in this population.

The literature search was restricted to six scientific databases. There is a possibility that some references were not captured in the search. However, these databases were chosen for their extensive coverage of veterinary science journals (94) and thus should have reduced the odds of missing a relevant paper. Although there was no restriction regarding year of publication the retrospective nature of the study might have conditioned data retrieve. Even if authors were still reachable databases were sometime no longer available. Nine papers were not accessible through our methodology. Additionally data could not be retrieved in twelve papers. This could have introduced bias into our analysis, but we do not know the direction of the bias nor the extent due the information lacking.

CONCLUSION

Our pooled lameness frequency estimates indicated high levels of the disease with ∼30% of British dairy cattle suffering from this ailment at any one moment in time. This analysis will be useful for investigations on the economic impact of lameness on British dairy cattle, by providing information on the burden of lameness, a key parameter for study of Animal Health Economics.

A diversity of detection and classification methods are used for collecting lameness data in the UK. This brings about inconsistency in the existing literature on the subject that hamper results comparison, limiting our ability to see if lameness is changing over time, be it for the purpose of assessing the effectiveness of an intervention or solely for monitoring lameness trend, and to understand lameness impact with precision. The use of artificial intelligence for identifying and monitoring lameness cases could offer objectivity and reliability compared with other lameness detection and classification methods, namely the mobility scoring systems and farm records.

The development and implementation of data collection systems that can offer reliable and standardized information are essential for the decision-making in the realm of animal health management.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

The main author was responsible for the systematic literature review, data management and analysis, development of risk bias assessment tools, and for the elaboration of the document. MB was involved in the reference screening and selection and reviewed the manuscript. PK was involved in the development of the code on R software program for the analysis and reviewed the manuscript. HC provided insights on the statistics around meta-analysis and helped guiding the analysis plan. DR contributed with his experience with meta-analysis and guiding the analysis plan. GO contributed with his experience in lameness research and reviewed the document. JR has oversight on the research in general. All co-authors have revised the paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2020.00542/full#supplementary-material

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Modeling *Salmonella* Spread in Broiler Production: Identifying Determinants and Control Strategies

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The presence of *Salmonella* spp. in broiler production is a food safety concern as the bacterium can be transmitted to humans via contaminated meat and derived products. Salmonella detection in litter at the pre-slaughter period has been linked to increased odds of contaminated broiler carcasses and meat derived products. To determine risk factors related to farm and broiler house characteristics and management practices, this study uses a unique longitudinal data set from a Brazilian integrated broiler enterprise, which contains official results of *Salmonella* spp. isolation from drag swabs collected at the end of the grow-out period. A Bayesian hierarchical spatio-temporal model found significant spatial and time influence on the odds of isolating *Salmonella* spp. from litter as well as significant effects from the size of a broiler house, total housing area per farm, type of broiler house, and number of litter recycles. Results indicate that recycling litter beyond 6 rearing cycles significantly increased the odds of isolating Salmonella before slaughter, and the bacterium was more likely to persist in conventional broiler houses, compared to broiler houses with controlled environment. Evidence of a potential principal-agent problem was also found in setting strategies to control the bacterium from litter, which suggests strong incentives to adopt the strategies aiming to reduce prevalence of the bacterium in the integrated enterprise. Our findings could be used to develop alternative measures to reduce the risk of persistence of the bacterium in the broiler production chain.

Keywords: *Salmonella*, broiler chicken, risk analysis, Bayesian hierarchical model, principal-agent problem

INTRODUCTION

Poultry meat is currently the world's most consumed and affordable meat type among animal-source. For the coming decade, per capita consumption of poultry meat is expected to increase by 5.5% worldwide, highlighting the importance of this commodity to food security, and protein availability (1). However, consumption of contaminated poultry meat was reported to cause 20.6% of foodborne diseases in the US between 1998 and 2008, among which *Salmonella* spp. was one of the main etiological agents (2).

Salmonella is a natural inhabitant of the gastrointestinal tract (GIT) of birds and can be introduced into the production system through several ways like contaminated feed or water, live vectors, contaminated litter, and even humans via contaminated boots or tools (3). Therefore, to effectively control the bacteria within a poultry enterprise, many critical control points involving different production stages must be properly observed from the parent stock, feed production, transportation, on-farm interventions and finally at the processing plant. In this regard, major efforts must be directed to reducing the bacterial load entering the processing plant, as cross contamination is a major source of bacterial detection at this level (4–6).

Healthy poultry frequently harbor Salmonella, and the transmission of the bacteria from meat and contaminated eggs is suggested as the main risk factor for human contamination. Effort involving surveillance, biosecurity, and vaccination has been related to substantial reduction in salmonellosis cases in Europe, highlighting the importance of adopting effective control measures in poultry and egg production, focusing primarily on serotypes related to human diseases like *Salmonella Enteritidis* and *Salmonella Typhimurium* (7).

Several risk analysis and modeling frameworks were performed to identify and suggest control measures for the risk of foodborne disease caused by Salmonella from broiler chicken (8–10), layers (11), pigs (12–14), and dairy cattle (15, 16).

Hygiene practices targeting bacterial elimination and prevention of contamination are constantly found to be interventions providing the greatest benefits in reducing prevalence at both production sites and processing plants (17, 18).

Epidemiological models have been used to model the spread of salmonella in many livestock production systems (12, 14–16, 19, 20). Most of these studies, however, have not accounted for dynamic decisions within the production system and are unable to estimate important parameters related to transmission and prevalence of diseases. The studies tend to rely heavily on assumptions, which makes the results fragile from applied perspectives. Furthermore, the lack of information from field controlled trials or field observations collected in a consistent manner is a major drawback when attempting to model real-life scenarios (21), underscoring the need to incorporate field data into a modeling framework. Such a task, however, is not trivial once not all firms keep a consistent scheme of data collection or are willing to disclose information.

When it comes to modeling the spread of salmonella within a broiler enterprise, it is crucial to have data of bacterial presence from different stages of production. The data are traceable across different production units and are repeated measurements from different farms throughout the processing plant. Such information allows the estimation of the likelihood of detecting the bacteria as a function of determined risk factors, aiming to further improve the control and ultimately eradicate the infection with evidence-based decision making. This information can be further applied to a commonly used epidemiological model to assess the optimal control measures given a set of available alternatives applicable to the specific enterprise.

However, when dealing with repeated measurements across time, temporal, and spatial autocorrelation must be accounted for to identify risk factors related to the occurrence of salmonella. It is intuitive that a poultry house that is positive to salmonella infection is more likely to remain positive if disinfection protocols are not properly applied, which will be translated into time autocorrelation. Similarly, a poultry house that is located closer to one that is positive for *Salmonella* spp. is more likely to be contaminated by vectors or fomites than poultry houses that are more spatially isolated. This neighborhood effect will ultimately be a cause of spatial autocorrelation.

The presence of spatial and temporal autocorrelation are problematic when fitting logistic regressions as the assumption of independent and identically distributed (i.i.d.) errors is violated, which especially affects the statistical significance of risk factor estimates. Furthermore, when evaluating risk factors for a determined biological agent, it may be of interest to identify and account for spatial patterns across time. Most studies evaluating risk factors for the presence of *Salmonella* spp. in livestock tend to consider random effects attributed to the farm or one specific region (6, 8, 22, 23). Few studies use longitudinal data, and most studies do not account explicitly for spatial autocorrelation.

Our study defines risk factors among farm characteristics and management practices consistently controlled by an integrated broiler enterprise related to the isolation of *Salmonella* spp. from litter in the grow-out period. We estimate a spatio-temporal Bayesian hierarchical binomial logistic regression model using field data of *Salmonella* spp. isolation in broiler houses from different farms in the south region of Brazil. The model captures the spatial and temporal patterns in Salmonella occurrence via random effects, while setting conditional autoregressive (CAR) priors. The probability of salmonella detection is then defined to be a function of covariates pertaining to consistently recorded farm characteristics and practices and the random spatio-temporal effects. The article contributes to literature by determining the effect of farm characteristics (e.g., size of broiler house and type of broiler house), as well as management practices (e.g., litter recycle) on the probability of isolating *Salmonella* spp. from litter, while explicitly accounting for spatial and temporal sources of variations.

Model estimates are used to calculate odds ratio for each of relevant risk factors to identify determinants of *Salmonella* spp. spread and draw control strategies for policy implications. We also discuss optimal control measures from estimated parameters and expected probabilities and show the effect of interventions related to litter recycles on the enterprise expected return using a partial budget and net present value (NPV).

MATERIALS AND METHODS

Data

The dataset comprises results of isolation of *Salmonella* spp. in litter of 417 different broiler flocks, collected from 139 broiler houses serving a vertically integrated company located in a south region of Brazil. The data of *Salmonella* spp. isolation were recorded from three consecutive flocks of each broiler house, accounting for a total evaluation time of 195 days. Drag swabs samples were collected from the litter of every broiler house 15 days before slaughter (average rearing time was 45 days). The collection was made by trained field technicians following standard protocols and analyzed by an accredited laboratory according to the recommendations described in the Ordinance 126 of November 3rd, 1995 (24), and following the program established by the Brazilian Ministry of Agriculture to control *Salmonella* spp. in broiler chickens and turkeys (25).

Briefly, the sampling procedure consists in dragging an assembly of at least three separate moistened 10 cm × 10 cm surgical gauze swabs, attached to a string stapled to a wooden spatula over the litter along the length of the broiler house, using the water and feeder lines as sectioning guides (26). The samples are then placed in transport media and immediately sent for analysis.

Spatial location of each broiler house was recorded using global positioning system (GPS) coordinates. The coordinates were then used to identify neighbors of every poultry house by Euclidean distance, using a circle of 20 km from each broiler location as a cutoff point. Under this specification, the obtained neighborhood matrix reveals an average number of links of 33.71 for each broiler house. Three broiler houses were the most connected with 63 links, while two were the least connected with only 1 link. Average link distance was 11.45 km[1], and median distance was 11.89 km.

Table 1 summarizes the farm characteristics adopted as covariates, used by the enterprise to characterize broiler houses, farms, and the practice of recycling litter. Size of broiler house relates to the total area of the broiler house in thousands of square meters. This is a continuous variable and ranges from 900 m^2 to 5,400 m^2, with mean value across all farms of 2,230 m^2. Number of broiler houses per farm was also a continuous variable ranging from one to four, with mean 1.52, which records the number of different broiler houses under the same farm unit. A dummy variable to indicate whether the broiler house was located on a farm with a single broiler house (0) or on a farm with multiple broiler houses (1) was included to identify possible management effects, as multiple broiler house farms tend to be more specialized. Total housing size is a continuous variable that the enterprise uses to measure the total broiler production area, in square meters, of the farm and is obtained by summing the areas of broiler houses in that particular farm. This variable ranges from 1,200 m^2 to 14,400 m^2, with mean value of 3,940 m^2.

Type of broiler house is a categorical variable used to characterize broiler houses across farms and is related to the structure and age of the building, type of equipment and isolation. Type 1 and type 2 broiler houses are conventional houses, with lateral curtains for insulation and ventilation, sprinklers, fans, automatic feeders, and drinkers. Main difference between types 1 and 2 houses relates to the age of the building, which is >5 years for type 1 and <5 years for type 2. Type 3 houses are those with negative pressure and controlled environment, with evaporative panels, automatic drinkers, and feeders.

TABLE 1 | Description of farm characteristics and practices adopted as covariates.

Covariate	Type	Code	Description
Size of broiler house (1,000 m^2)	continuous	House size	Min = 0.90, average = 2.23, max = 5.40
Number of broiler houses/farm	continuous	N_houses	Min = 1.00, average = 1.52, max = 4
Single house	categorical	single	Dummy variable taking the value of 0 if farm has only one broiler house and 1 if farm has 2 or more broiler houses
Total housing size (1,000 m^2)	continuous	Total housing size	min = 1.20, average = 3.94, max = 14.40
Type of broiler house	categorical with three levels	Type1, Type2, Type3	1-Old building with curtains, 2-New building with curtains, 3-New building with climate control
Number of litter recycles	continuous	Litter_use	min = 1.00, average = 5.72, max = 22.00
Presence of livestock	categorical	Livestock	1 if present, 0 otherwise
Presence of dogs	categorical	Dogs	1 if present, 0 otherwise
Presence of crop areas	categorical	Crops	1 if present, 0 otherwise

The number of litter recycle indicates the number of times the litter used in one flock is treated in the between flock period and used on the next flock, with little or no addition of new litter. The average number of recycles is 5.72, ranging from 1 to 22 recycles. Wood shavings are used as bedding material in this enterprise and compose the litter. Other variables recorded are categorical and relate to the presence (1) or absence (0) of livestock, dogs or crop areas in the farm where the broiler house is located.

Out of the 139 evaluated broiler houses, 45, 74, and 77 were found to be positive for *Salmonella* spp. at the end of the first, second and third rearing cycles, accounting for an estimated raw prevalence of 32.37, 53.32, and 55.39%, respectively.

Model Specification

Each of the broiler houses in this study is considered a unique spatial unit k, with k = 1, . . . , K = 139, defined by a GPS location. Data on presence or absence of *Salmonella* spp. at the end of each t = 1,.., T = 3 rearing periods is recorded for every unit. Denoting by θ_{kt}, the probability of detecting *Salmonella* spp. in litter of the k-th broiler house at time *t*, a Bayesian hierarchical logit model is described as:

$$\ln\left(\frac{\theta_{kt}}{1-\theta_{kt}}\right) = \mathbf{X}_{kt}{}'\beta + \varphi_{kt} + \delta_t. \quad (1)$$

The logit probabilities of *Salmonella* spp. detection are modeled as a liner combination of a $p \times 1$ vector of covariates $\mathbf{X}_{kt}$, and spatial φ_{kt}, and temporal δ_t random effects, where p represents

[1]The cutoff value of 20 km will measure how many broiler houses are located within up to 20 km of other broiler houses. On average, the distance between broiler houses was 11.45 km.

covariates described in **Table 1**, and their respective vector of regression parameters β.

It is assumed that β follows a multivariate normal distribution and a diffuse multivariate normal prior distribution is specified: $\beta \sim N(0,\ 1,000\mathbf{I})$, where $\mathbf{I}_{p\times p}$ is the identity matrix.

The spatial random effect φ_{kt} and temporal random effect δ_t model spatial and temporal trends and autocorrelation in the data after accounting for the covariate effects. Spatial autocorrelation is controlled by a symmetric K × K neighborhood weight matrix $\boldsymbol{W} = (w_{kj})$, where w_{kj} represents spatial closeness between spatial units (S_k, S_j), and w_{kj} is non-zero if they share a common border and zero otherwise, and $w_{kk} = 0$ for all k. Temporal autocorrelation is controlled by a binary N × N temporal neighborhood matrix $\boldsymbol{D} = \left(d_{tj}\right)$, where $d_{tj} = 1$ if | j–t | = 1 and $d_{tj} = 0$ otherwise.

It is specified as:

$$\varphi_t \sim N\left(0,\ \tau_t^2 \boldsymbol{Q}\left(\boldsymbol{W}, \rho_S\right)^{-1}\right) for\ t = 1, \ldots, N, \tag{2}$$

where $\varphi_t = (\varphi_{1t}, \ldots, \varphi_{kt})$ is the vector of all spatial random effects at period t, and the spatial autocorrelation in the data is modeled by the matrix $\boldsymbol{Q}\left(\boldsymbol{W}, \rho_S\right) = [\rho_S(diag\left(\boldsymbol{W1}\right) - \mathbf{W}) + (1-\rho_S)\,\mathbf{I}]$, where 1 is a K ×1 vector of 1′s, so that diag (W1) is a diagonal matrix with diagonal elements equal to the row sums of W. W and $\mathbf{I}_{K\times K}$ are the neighborhood and identity matrices, respectively. The full conditional specification of φ_{kt} is then:

$$\varphi_{kt}|\varphi_{-kt}, \boldsymbol{W}, \rho,\ \tau_t^2 \sim N\left(\frac{\rho_S \sum_{j=1}^{K} w_{kj}\varphi_{jt}}{\rho_S \sum_{j=1}^{K} w_{kj} + 1 - \rho_S},\ \frac{\tau_t^2}{\rho_S \sum_{j=1}^{K} w_{kj} + 1 - \rho_S}\right), \tag{3}$$

where $\varphi_{-kt} = \left(\varphi_{1,t}, \ldots, \varphi_{k-1,t}, \varphi_{k+1,t}, \ldots, \varphi_{K,t}\right)$.ρ_S measures the strength of spatial autocorrelation and is assumed to be constant over time, as variances τ_t^2 are allowed to change temporally, thus, capturing changes on spatial variability.

For the temporal random effect, it is specified as:

$$\delta_t|\delta_{-t},\ \boldsymbol{D} \sim N\left(\frac{\rho_T \sum_{j=1}^{N} d_{tj}\delta_j}{\rho_T \sum_{j=1}^{N} d_{tj} + 1 - \rho_T},\ \frac{\tau_T^2}{\rho_T \sum_{j=1}^{N} d_{tj} + 1 - \rho_T}\right), \tag{4}$$

where $\delta = (\delta_1, \ldots, \delta_N)$. ρ_T measures the strength of temporal autocorrelation and the temporal random effects capture the overall temporal trend in the probability of isolating *Salmonella* spp. in litter across all broiler houses. The spatial random effects model was proposed by Leroux et al. (27), while the temporal random effects were described in Besag et al. (28).

Priors are specified for parameters from Equations (3) and (4) as:

$$\tau_1^2, \ldots, \tau_N^2,\ \tau_T^2, \sim \text{Inverse} - \text{Gamma}\,(1, 0.01\,)$$
$$\rho_S, \rho_T \sim \text{Uniform}\,(0, 1)\,. \tag{5}$$

The distributions and parameter values in Equation (5) are chosen because they provide flat and conjugate priors, as described in Lee et al. (29). Sampling from the posterior distributions is obtained using Markov Chain Monte Carlo simulation with Gibbs sampling and Metropolis-Hastings algorithms. Computations are made in the R software, using package CARBayesST.

Spatial dependence is evaluated by first fitting the Bayesian hierarchical model specified in equation (1) without including random effects. Residuals are recovered and used to compute Moran's I (30) statistics, performing permutation tests on the residuals separately for each year. The null hypothesis tested is of no spatial autocorrelation and the alternative hypothesis is of positive spatial autocorrelation. Temporal autocorrelation at lag 1 was also computed from the residuals using a Lagrange multiplier test for serial correlation (31) across all locations (null hypothesis of no serial autocorrelation, and alternative hypothesis of autocorrelation of order 1).

To select relevant covariates, we first estimate equation (1) including all variables in **Table 1** with relevant interactions. These covariates are included to represent the standard poultry environment in Brazil to incorporate risk factors that are frequently examined in previous studies (23, 32, 33). After estimating the model, variables with insignificant estimates were removed from model specification. The model was then re-estimated without the insignificant covariates. This exercise was done iteratively until the final model was obtained. The Deviance Information Criterion (DIC), an information criterion that accounts for model goodness of fit while penalizing complexity (34) was also used to compare different specifications. DIC can be easily calculated from posterior samples and is preferred over other information criteria (like Akaike information criterion and Schwarz-Bayes information criterion) for being more appropriate in hierarchical models. This model selection approach is commonly applied in the epidemiological literature (6, 23, 35).

Model estimates were obtained after generation of 200,000 samples, following a burn-in period of 50,000 samples. Convergence for the chain of each posterior distribution was assessed to have been reached using Geweke's statistics (36), which is based on the normal approximation and measures the sampled mean value of the first 10% of the chain as compared to the last 50%. If the calculated statistic is >|1.96|, there is evidence of poor convergence, as calculated sample means at the beginning of the chain are substantially different than calculated mean at the end of the chain. Subsequently, 150,000 samples were generated, where every 10th draw was stored and the rest discarded to remove the autocorrelation, leaving inference based on 15,000 samples.

Economic Analysis

We use production cost and revenue estimates reported by Miele et al. (37) for an integrated broiler enterprise in the studied region and provide an example of how the model estimates and Odds Ratios can be translated into economic terms. The costs of litter replacement per flock and total labor costs as a proportion of total working costs[2], and expected return per flock over total capital costs[3] are calculated considering a 6% annual return rate, following Miele et al. (37). We compare the impact of positive flocks on expected return over total working costs.

The expected return is calculated adopting a baseline scenario for each type of broiler house, assuming that litter will be completely replaced after six cycles, a common practice considered for the expected return and working costs calculation per flock (37). On the integrated system, the cost of litter replacement is a responsibility of the producers. Therefore, to increase return, there may be an incentive to recycle litter beyond the recommended number of cycles to reduce working costs and therefore increase profit.

Assuming that litter recycles is the only risk factor responsible for *Salmonella* spp. transmission and persistence, we want to evaluate how the dynamics of potential cost reduction may affect incentives to recycle litter, considering a 2-year (12 rearing cycles) interval.

We assume producers are allowed to choose between two possible strategies of litter replacement: strategy 1 (baseline) is to follow the recommendation of the integrator and recycle litter for six rearing cycles, than replace it completely, and strategy 2 (baseline+additional recycle) is to recycle litter beyond six rearing cycles, replacing it completely only after 12 rearing cycles. We assume that positive flocks will have a 40% penalty reduction on total return[4], which will be transferred to the farmer according to the proportion of produced positive flocks only if litter is recycled more than 6 times.

The problem faced by the producer may be defined by:

$$\max_{st} \sum_{t=1}^{12} \frac{NR(st)_t}{(1+\ r)^t} \tag{6}$$

Where *st* is a discrete choice related to the strategy to be chosen of follow the recommendation of the integrator, recycling litter only 6 times, then replacing it and follow with an additional six recycles (strategy 1-baseline), or recycling litter more than 6 times (strategy 2-baseline + additional recycle), $NR(st)_t$ is the net return at cycle t obtained after following each litter recycle strategy for each of the broiler houses, $r = 1\ \%$ is the discount rate.

We see that for $t = 1$ to $t = 6$, $NR(st)_t$ is the same for both strategies within each broiler house, as no penalties are applied for positive flocks, while for $t = 7$ to $t = 12$, $NR(2)_t$ can be calculated as follows:

$$NR\,(2)_t = ER_t \times \left(1 - \frac{1}{2}(\hat{\theta}_{t\frac{N}{2}} + \hat{\theta}_{t\mathbf{1}+\frac{N}{2}}) \times 0.4\right), \tag{7}$$

[2]Total working costs are defined by the author as the sum of labor, litter, wood, and electricity, maintenance, insurance, propane, paper for housing chicks, quick lime, extras (including other utilities), depreciation, and environmental costs (licenses).
[3]This cost includes previously reported costs plus investment in buildings and equipment.
[4]The enterprise does not have any policy to implement discounts for positive flocks or underperformance. 40% discount was arbitrarily selected to imply a severe penalty.

TABLE 2 | Test results for spatial autocorrelation at each rearing cycle (time period).

Rearing cycle	Observed rank	Test statistic[a]	*p*-value
1	1,252	−0.023	0.874
2	1,243	0.024**	0.048
3	9,513	0.027**	0.033

[a]*Moran's I test statistic was obtained after 10,000 simulations. H_0 = no spatial autocorrelation, H_1 = positive spatial autocorrelation.*
****Denote significance at the 5% level.**

Where ER_t is the expected revenue (in %) at time t obtained from Miele et al. (37), $\hat{\theta}_{t\mathbf{N}} = \frac{exp(\mathbf{X}_t^T\beta)}{1+exp(\mathbf{X}_t^T\beta)}$ is the ordered *N-th* draw of the posterior density of the estimated probability of isolating *Salmonella* spp. when the covariates **X** are litter recycles (Litter_use and Litter_use^2) and type of broiler house (defined in **Table 4**), with $N = 1,\ldots,15{,}000$.

We present the calculation of cost per flock of litter replacement for each type of broiler house, as well as the expected return per flock and expected loss from positive flocks for recycles >6 periods. We then show calculations of net present value, obtained from Equation (6) for both strategies and discuss its implications.

RESULTS

Table 2 shows the presence of positive spatial autocorrelation in second and third rearing cycles based on Moran's *I*-test statistics (**Table 2**), confirming the adequacy of a spatial model. Temporal autocorrelation was also detected (0.22 on average across all locations—not shown in tables), suggesting the presence of positive autocorrelation at lag 1.

The Bayesian posterior medians and 95% credible intervals for equation (1), reported in **Table 3**, show that all covariates except the number of broiler houses per farm and the dummy variable indicating a single or multiple broiler house per farm, presence of livestock, dogs, or crops significantly affected the probability of isolating *Salmonella* spp. from litter. In a Bayesian setting, the posterior density is used to asses if an independent variable has a non-zero effect over the response by defining the 2.5 and 97.5% limits for the distribution, which is normally defined as the 95% credible interval. If this credible interval does not contain zero, then the effect of the independent variable may be understood as "significant" or non-zero. Interactions between type of broiler house and each of the numerical variables were also evaluated and found to be insignificant (results not shown for brevity)[5].

To allow for non-linear responses of the numeric variables, a quadratic term was included, and was found to be significantly different from zero only for size of broiler houses and litter reutilization as shown in **Table 3**[6].

[5]DIC for model including interactions was 549.66.
[6]The quadratic functional form was also tested for number of broiler houses and total housing size but was not preferred over the linear functional form. DIC for

TABLE 3 | Bayesian hierarchical logit posterior medians and credible intervals including all covariates described in **Table 1**[a].

Variable	Parameter	Median	2.5%	97.5%	Geweke[b]
Intercept	β_0	−2.823	−4.852	−0.608	0.3
House size	β_1	3.043	1.340	4.651	−0.6
House size^2	β_2	−0.314	−0.557	−0.058	0.7
Litter_use	β_3	−0.209	−0.452	0.006	1.9
Litter_use^2	β_4	0.017	0.001	0.036	−1.9
Total housing size	β_5	−0.349	−0.536	−0.185	0.3
Type2	β_6	−1.169	−2.172	−0.129	0.3
Type3	β_7	−1.890	−3.186	−0.457	0.4
N_houses	β_8	0.392	−0.336	1.094	−0.6
Single	β_9	−0.261	−1.168	0.621	0.6
Livestock	β_{10}	−0.723	−1.597	0.113	0.2
Dogs	β_{11}	0.555	−0.231	1.364	−0.3
Crops	β_{12}	0.000	−0.661	0.648	0.8
	DIC[c] = 535.97				

Dependent variable is the isolation of Salmonella spp. in litter (n = 417).
[a]Random effects estimates are not shown.
[b]Geweke diagnostic: values lower than |1.96| suggest good mixing of the chains.
[c]Deviance information criterion.

TABLE 4 | Bayesian hierarchical logit posterior medians and credible intervals including only significant covariates and specific random effects.

Variable	Parameter	Median	2.5%	97.5%	Geweke[a]
Intercept	β_0	−2.427	−4.285	−0.685	0.9
House size	β_1	2.921	1.385	4.541	−0.9
House size^2	β_2	−0.310	−0.543	−0.077	0.9
Litter_use	β_3	−0.227	−0.458	−0.017	0.2
Litter_use^2	β_4	0.018	0.002	0.037	−0.1
Total housing size	β_5	−0.281	−0.419	−0.159	0.6
Type2	β_6	−1.154	−2.193	−0.200	0.6
Type3	β_7	−1.921	−3.275	−0.697	0.8
Rearing cycle1	δ_1	−0.518	−0.884	−0.124	−0.6
Rearing cycle2	δ_2	0.189	−0.038	0.481	−0.3
Rearing cycle3	δ_3	0.312	0.038	0.617	0.7
Spatial var1	τ_1^2	0.005	0.001	0.028	0.5
Spatial var2	τ_2^2	0.005	0.001	0.037	−0.3
Spatial var3	τ_3^2	0.005	0.001	0.033	−1.1
Time var	τ_T^2	0.113	0.010	0.807	0.0
Spatial autocorrelation	ρ_S	0.224	0.011	0.691	0.7
Time autocorrelation	ρ_T	0.380	0.021	0.896	0.3
	DIC[b] = 530.01				

Dependent variable is the isolation of Salmonella spp. in litter (n = 417).
[a]Geweke diagnostic: values lower than |1.96| suggest good mixing of the chains.
[b]Deviance information criterion.

Table 3 also shows the posterior median and credible intervals for all covariates listed in **Table 1**, as well as Geweke statistics. The effect of number of broiler houses per farm (N_houses) and whether the farm has one or multiple broiler houses (single) was not different from zero. The same was true for the presence of livestock, dogs, or crops. Geweke statistics for all posterior distributions reveals good mixing of samples and provide evidence of converge of the chains. Random effect estimates are not shown in **Table 3** for brevity but were also accounted for during model selection.

After excluding insignificant covariates shown in **Table 3** and re-estimating the model from equation (1), the DIC from **Table 4** indicates that the new specification is indeed preferred over the latter (530.01 for model from **Table 4** vs. 535.97 for model from **Table 3**). **Table 4** reports that a quadratic effect between the size of broiler house and the number of litter reutilizations were identified but with opposite responses: size of broiler house was found to increase the odds of isolating *Salmonella* spp. in litter, peaking for broiler houses between 4,000 and 5,000 m^2 and decreasing thereof. Notice that the average size is 2,230 m^2. This effect is better observed from **Figure 1**, where the posterior distribution of the calculated Odds Ratio (O.R.) of size of broiler house, with respect to the mean value, is graphed.

Number of litter recycles decreased the odds of isolating *Salmonella* spp. in litter up to five to six recycles and increased thereof, while the average number of recycles is 5.72 times. The posterior distribution with credible intervals of the calculated O.R. of number of litter recycles is graphed in **Figure 2** for better reference.

Total housing size had a linear negative effect on the log of odds of isolating *Salmonella* spp. in litter, as viewed by the negative value of the posterior median for this variable (**Table 4**). To better understand this effect, we calculate the posterior distribution and plot median values and credible intervals of the O.R. of the total housing size value with respect to the mean value (3,940 m^2) and depict the response in **Figure 3**. It is clear that farms with bigger housing capacity, not necessarily bigger houses, are less likely to be tested positive for *Salmonella* spp. in litter than farms with smaller capacity. One possible explanation for this effect may be that farms with more housing area tend to be more specialized, leading to better management practices during and between the rearing period. Although technical support is provided by the integrator, every farmer is responsible for carrying out husbandry and disinfection procedures under regular supervision of a qualified technician, which can ultimately lead to differences not only on the odds of isolating *Salmonella* spp. but also on performance parameters[7].

Categorical variables for broiler house type reduced the probability of detection of *Salmonella* spp. Odds ratio (O.R.) calculated for a type 2 broiler house reveals that the odds of isolating *Salmonella* spp. from litter of this type of building is 68% lower (O.R.≅0.32) than from a type 1 building, with credible

model presented in **Table 3**, including quadratic terms for all numeric variables was 536.46. For brevity, estimates are not shown in **Table 3**.

[7]Data related to performance parameters, like feed efficiency, daily gain, and mortality could help clarifying the reason why farms with larger housing area, but not necessarily with more houses, were less likely to have the bacterium isolated from litter. However, due to confidentiality issues, this data could not be provided.

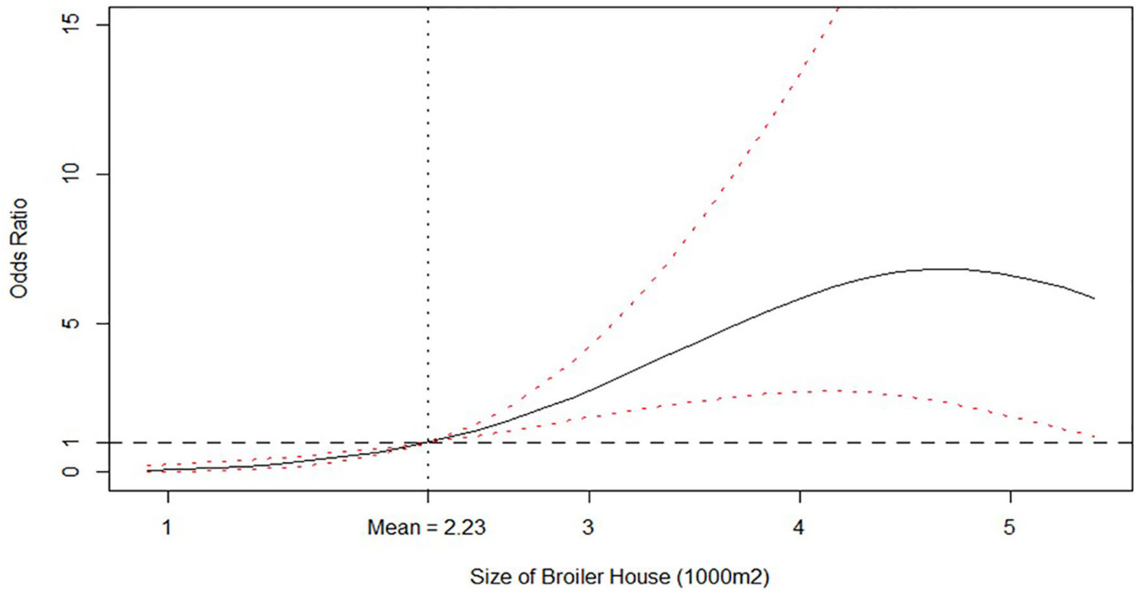

FIGURE 1 | Odds ratio relationship between size of broiler house (1,000 m^2) and Probability of isolating *Salmonella* spp. from litter. Odds ratio is relative to the mean value, which is shown by the vertical dashed line. Solid line is the posterior median odds ratio and red dashed lines are 95% credible intervals. Horizontal dashed line shows odds ratio = 1 for reference.

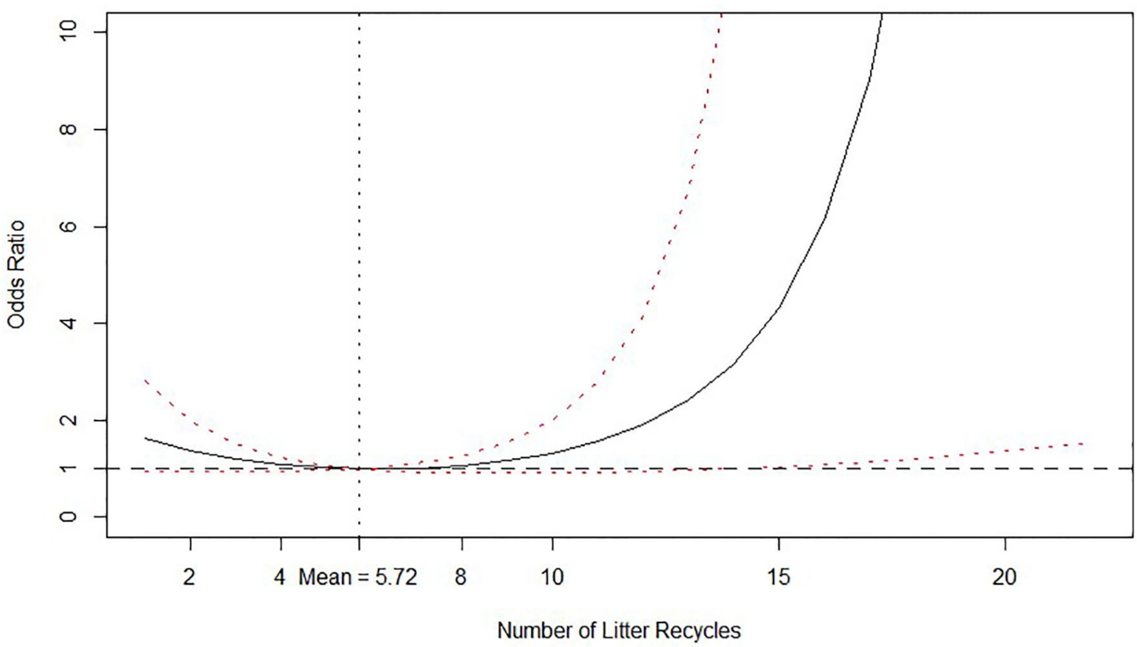

FIGURE 2 | Odds ratio relationship between number of litter recycles and probability of isolating *Salmonella* spp. from litter. Odds ratio is relative to the mean value, which is shown by the vertical dashed line. Solid line is the posterior median odds ratio and red dashed lines are 95% credible intervals. Horizontal dashed line shows odds ratio = 1 for reference.

intervals ranging from 18% (O.R.≅0.82) to 89% (O.R.≅0.11). Similarly, the odds of isolating *Salmonella* spp. from type 3 buildings is 85% lower (O.R.≅0.15), with credible intervals ranging from 50% (O.R.≅0.5) to 96% (O.R.≅0.04). These relationships are graphed in **Figure 4**, where the posterior distributions of the calculated O.R. with respect to type 1 houses,

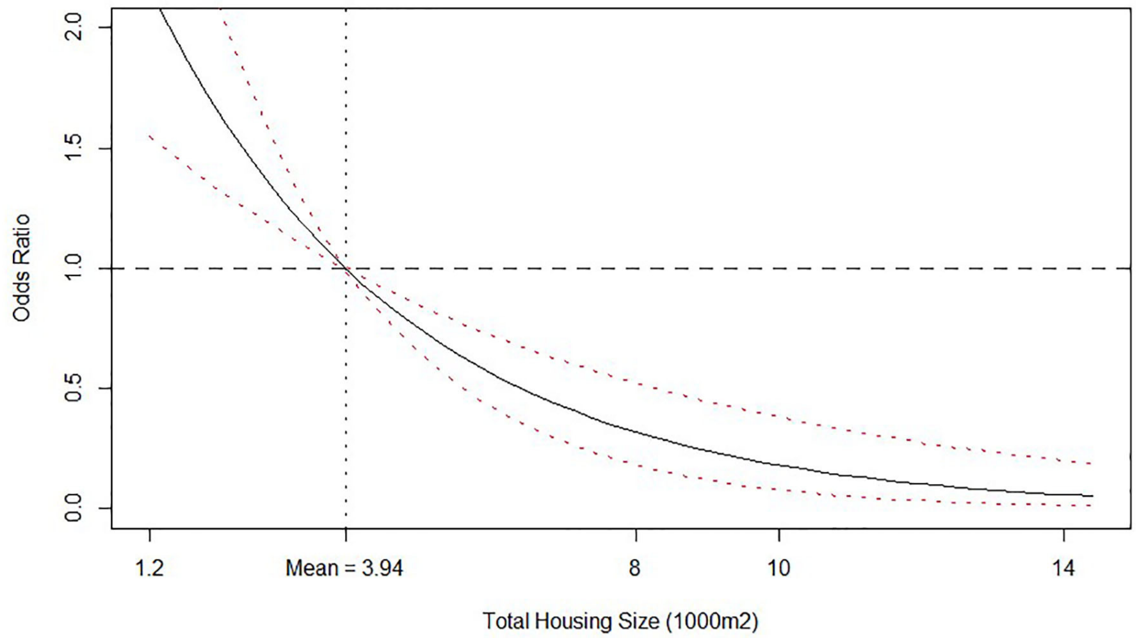

FIGURE 3 | Odds ratio relationship between Total housing size (1,000 m^2) and probability of isolating *Salmonella* spp. from litter. Odds ratio is relative to the mean value, which is shown by the vertical dashed line. Solid line is the posterior median odds ratio and red dashed lines are 95% credible intervals. Horizontal dashed line shows odds ratio = 1 for reference.

FIGURE 4 | Violin plots showing the posterior density of the estimated Odds Ratio relationship between types of broiler house 2 and 3 with respect to type1 and probability of isolating *Salmonella* spp. from litter. Horizontal lines inside plots represent posterior medians and 95% credible intervals.

FIGURE 5 | Violin plots showing the posterior density of the average estimated probability of isolating *Salmonella* spp. at the end of each time point for all types of broiler houses. Horizontal lines inside plots represent posterior medians and 95% credible intervals.
Theta_hat $= \hat{\boldsymbol{\theta}}_{\mathbf{t}} = \frac{\exp(\overline{\mathbf{X}}_t^T \beta + \delta_t)}{1+\exp(\overline{\mathbf{X}}_t^T \beta + \delta_t)}$, for $\overline{\mathbf{X}}_{\mathbf{t}} = \frac{\sum_{k=1}^{K} \mathbf{X}_{kt}}{\mathbf{K}}$.

with median values and 95% credible intervals are shown in violin plots.

Regarding type of broiler house, in this study, conventional broiler houses (with lateral curtains used to control temperature and air flow) were classified into two categories: type 1 and type 2. The main difference attributed between both relates to the age of the building, that for type 1 houses was >5 years, while for type 2 houses was lower than 5 years. Type 3 houses, however, are broiler houses without curtains, but with evaporative cooling systems, which means that there is no direct contact with outdoor environment and the entrance of wild birds or rodents is markedly reduced.

The estimated time specific effects (δ_t) revealed a positive trend on the probability of isolating *Salmonella* spp. in litter, as observed on the graphical representation from **Figure 5** of the estimated probability of isolating *Salmonella* spp. in litter for each type of broiler house across the evaluation period.

Figure 5 clearly shows a similar increase in estimated probability of isolating *Salmonella* spp. from litter of all types of broiler houses, but also highlights the difference in probability between houses, which seems to remain similar throughout the study. When looking at posterior median, type 3 broiler houses calculated probabilities were 60–70% lower than type 1, while calculated probabilities for type 2 houses were 36–50% lower than type 1.

Posterior median of correlation coefficients and variances (**Table 4**) show evidence of positive spatial autocorrelation ($\rho_S = 0.2247$) and time autocorrelation ($\rho_T = 0.3808$). Estimates for spatial variation for every time period (τ_t^2) were very similar, suggesting no significant differences on variance of the probability of detection of *Salmonella* spp. across space.

For comparison purposes, we show the covariate estimates without accounting for temporal or spatial autocorrelation in **Table 5**. Although the comparison of Bayesian estimates with estimates obtained using the frequentist approach are not appropriate, we observe that estimated coefficients were overall smaller than the obtained posterior medians when assuming residuals are i.i.d, and the coefficients for litter recycles were only marginally significant. This will carry much uncertainty on the determination of relevant risk factors and especially for the case of litter recycles, will lead to unreliable standard errors and consequent estimation of confidence intervals for O.R.

TABLE 5 | Logit estimates with covariates and interaction terms without accounting for spatial and temporal effects.

Covariate	Estimate[a]	Std. error	*p*-value
Intercept	−2.263**	0.912	0.013
House size	2.723***	0.779	0.001
House size^2	−0.290**	0.115	0.012
Total housing size	−0.263***	0.063	<0.001
Type2	−1.055**	0.479	0.027
Type3	−1.785***	0.625	0.004
Litter_use	−0.186*	0.109	0.086
Litter_use^2	0.014*	0.008	0.097

Dependent variable is the isolation of Salmonella spp. in litter (n = 417).
[a]Maximum likelihood estimation obtained under the generalized linear model framework with logit link function.
****Denote significance at the 1% level.*
***Denote significance at the 5% level.*
**Denote significance at the 10% level.*

TABLE 6 | Posterior medians and credible intervals for the calculated probabilities of isolating *Salmonella* spp. from litter according to the number of litter recycles ($n = 15{,}000$ samples).

Number of recycles	Median	2.5%	97.5%
1	0.448	0.396	0.496
2	0.406	0.316	0.494
3	0.374	0.260	0.495
4	0.351	0.222	0.497
5	0.337	0.199	0.497
6	0.333	0.188	0.501
7	0.336	0.187	0.509
8	0.347	0.196	0.519
9	0.367	0.213	0.555
10	0.397	0.239	0.585
11	0.437	0.270	0.626
12	0.488	0.303	0.682

Regarding cost calculations for the economic analysis, **Table 6** reports the calculated posterior medians and 95% credible intervals for the probabilities of isolating *Salmonella* spp. from litter according to the number of litter recycles. The calculated probabilities in **Table 6** are consistent with the O.R. relationship depicted in **Figure 2**. It is clear from **Table 6** and **Figure 2** that setting the number of recycles in six provides the lowest probability of isolating *Salmonella spp.*

Table 7 reports the cost calculations related to litter recycles for each type of broiler house evaluated in this study, and reported in Miele et al. (37). Costs and returns are expressed as a proportion of total working cost per broiler house. Expected loss from positive flocks shows how much discount would be applied to those producers who decided to recycle litter beyond six periods.

For our example, we see that by recycling litter for an additional six cycles, the producer will be able to dilute the cost with litter replacement into 12 cycles (including first six cycles to which no penalty was applied) Such distribution of costs is clear when we observe cost/flock of litter replacement, which decreases for all types of houses, but is numerically greater for type 3 houses (column 2 from **Table 7**). The different cost structures for each broiler house indicates that there might be different incentives to recycle litter. **Table 8** shows that for broiler houses of type 1 and 3, using a discount rate of 1% per cycle, and considering the baseline scenario as $100 expected payment per flock for each type of broiler houses, producers will choose to extend recycle until 12 rearing cycles, as the calculated NPV, will be >12 equal payments. This decision will maximize expected NPV of producers but will also lead to a significant increase on the probability of detecting *Salmonella* spp. from litter.

DISCUSSION

Size of broiler house, also named house area in other studies (17, 22, 38), significantly influenced probability of detection of *Salmonella* spp. This covariate did not significantly affect the response in those studies, while it was linked to increase in O.R. in other studies in laying hens (8, 39). From a transmission perspective, it might be possible that bigger houses, housing a greater number of birds, would be more likely to, given a potential contamination, favor pathogen amplification. In the present study, although density could not be effectively recorded, the same average number of birds per square meter are housed for different types and sizes of broiler houses[8] in the enterprise. Furthermore, interactions between type and size of broiler house did not reveal significant effects, reducing the likelihood of a potential confounding between these variables.

Observations of reduced risk of *Salmonella* spp. positive flocks in the current study related to type of broiler house could be due to more stable and isolated environments on broiler houses of types 2 and 3. Such isolation is expected to reduce contamination from external sources vectored by birds, rodents or dust, which are constantly pointed as risk factors for *Salmonella* spp. contamination (6, 10, 35). This fact, linked to a potential greater commitment of the integrated producer on a higher fixed investment may be an explanation for the observed effect and may also explain the difference on O.R. between old and new buildings (types 1 and 2, respectively). Old buildings and old equipment are harder to disinfect, as they become worn out and with fixtures, favoring the accumulation of dirt, litter, and feces. Such effects, linked to a higher need for maintenance (replacing curtains, nets, disabling, and cleaning equipment) could lead to both an increased persistence of contamination, as well as an increased susceptibility for contamination from external sources (17, 40, 41). A similar explanation applies for the effect of total housing size and was already discussed.

When interpreting the difference in probabilities of detecting *Salmonella* spp. from different types of broiler houses across time,

[8]Normally, type 3 broiler houses, which have a controlled environment and more stable temperature and moisture conditions tend to accommodate higher densities, but this information was not fully disclosed for this study.

TABLE 7 | Calculated costs of litter replacement per flock, expected returns, gains, losses, and net return for each type of broiler house according to the number of litter recycles.

Type of broiler house	Cost/flock of litter replacement[a] %	Number of recycles	Expected return[b] %	Expected loss from positive flocks[c] %	Expected net return[d] [min %, median %]
Type 1	12.32	6 (baseline)	14.25	–	[14.25, 14.25]
	11.91	7	14.65	1.97	[10.56, 12.68]
	10.59	8	15.97	2.22	[11.37, 13.75]
	9.57	9	17.00	2.50	[11.97, 14.50]
	8.74	10	17.82	2.83	[12.42, 14.99]
	8.07	11	18.49	3.23	[12.68, 15.26]
	7.51	12	19.05	3.72	[12.74, 15.33]
Type 2	11.73	6 (baseline)	15.18	–	[15.18, 15.18]
	11.34	7	15.57	2.09	[11.28, 13.48]
	10.08	8	16.83	2.34	[11.98, 14.49]
	9.10	9	17.81	2.61	[12.54, 15.19]
	8.32	10	18.59	2.95	[12.95, 15.64]
	7.68	11	19.23	3.36	[13.19, 15.87]
	7.15	12	19.76	3.86	[13.22, 15.90]
Type3	14.61	6 (baseline)	15.36	–	[15.36, 15.36]
	13.10	7	16.86	2.27	[12.15, 14.59]
	11.54	8	18.43	2.56	[13.12, 15.87]
	10.32	9	19.65	2.88	[13.84, 16.76]
	9.35	10	20.62	3.27	[14.37, 17.35]
	8.55	11	21.42	3.74	[14.69, 17.67]
	7.89	12	22.08	4.31	[14.77, 17.77]

[a] *Cost estimated as a percentage of total working cost for each type of broiler house.*
[b] *Expected return calculated considering total capital cost and a 6% annual rate, and expressed as a percentage of total working cost according to the type of broiler house.*
[c] *Expected loss from positive flocks calculated by the product of the posterior median of the probability of isolating Salmonella (percentage of positive flocks) and the 40% revenue discount for positive flocks.*
[d] *Posterior distribution of net returns obtained by subtracting the expected return and the expected Loss related to litter recycles. Minimum and Median values are displayed.*

we see that although an overall increase on probabilities was observed, types 2 and 3 houses were relatively less affected than type 1. This finding indicates that one possible measure taken by the integrator to significantly reduce *Salmonella* spp. prevalence and potential losses at the end of the production chain will be to incentivize contracted producers to invest in new broiler houses or eventually contract with producers who have types 2 and 3 broiler houses.

Regarding Litter reutilization, it may be classified as a factor affecting persistence of contamination, because every broiler house's litter is commonly treated inside it in the between-flock period and hardly is exchanged with other broiler houses, even when in the same farm. The practice of recycling litter is common in Brazil due to the limited supply of wood shavings (the most common bedding material) and due to the high economic cost of replacing litter at the end of each cycle.

Persistence of *Salmonella* spp. in litter is well studied (9, 42) and known to be affected by moisture levels, temperature and ammonia levels during fermenting or composting, so that in aged litter (more recycled) higher levels of these factors are required to properly eliminate the bacterium (43–45). This behavior is reflected in the O.R. obtained for litter recycle, where a reduction on O.R. was observed with a subsequent increase. The initial reduction may be due to interactions of *Salmonella* spp. with other microorganisms colonizing litter in the early reutilizations: as less stablished is the microbiome of the litter, the less effect of competitive exclusion is observed, accounting for a relative higher presence of *Salmonella* spp. on first recycles, summed to the impacts of fermentation. At a certain point, however, fermentation starts to lose efficiency and persistence of *Salmonella* spp. is encouraged, as demonstrated in Kim et al. (45).

Implications of Research Findings

Using a spatio-temporal Bayesian hierarchical binomial logistic regression model, this study shows that the probability of detecting *Salmonella* spp. in litter of broiler houses in the grow-out period is significantly affected by size of broiler house, total housing area, type of broiler house, and number of litter recycles. To the author's best knowledge, it is the first study to evaluate risk factors related to *Salmonella* spp. isolation in broiler chicken litter in Brazil, and also to use data routinely and consistently collected by a broiler enterprise. Some authors assess the prevalence of specific Salmonella serotypes in the same region, but use pooled data (without accounting for spatial or time autocorrelation)

TABLE 8 | Net present value calculated for expected returns obtained for each type of broiler house.

Type of broiler house	Number of recycles	Expected net Return[a] %	Expected net return[b] ($)	NPV (baseline)[c]	NPV (baseline + recycles)[d]
Type 1	6 (baseline)	14.25	100	$1,125.51	$1,131.38
	7	12.68	88.98		
	8	13.75	96.49		
	9	14.50	101.75		
	10	14.99	105.19		
	11	15.26	107.08		
	12	15.33	107.58		
Type 2	6 (baseline)	15.18	100	$1,125.51	$1,121.95
	7	13.48	88.80		
	8	14.49	95.45		
	9	15.19	100.06		
	10	15.64	103.03		
	11	15.87	104.54		
	12	15.90	104.74		
Type3	6 (baseline)	15.36	100	$1,125.51	$1,171.36
	7	14.59	94.98		
	8	15.87	103.32		
	9	16.76	109.11		
	10	17.35	112.95		
	11	17.67	115.04		
	12	17.77	115.69		

[a] *Median value of expected net return described in* ***Table 7***.
[b] *Expected return in monetary terms assuming baseline value as $100.*
[c] *Net present value calculated using a discount rate of 1% per period and 12 equal payments of $100.*
[d] *Net present value calculated using a discount rate of 1% per period, 6 equal payments of $100 and the expected monetary returns depicted in column 4 for each type of broiler house.*

from different enterprises and report values between 5 and 11% (46–48). More recently, Voss-Rech et al. (42) evaluating nine broiler houses in the same region, showed that non-typhoidal Salmonella persisted in contaminated farms but did not link the results to risk factors.

In our study, covariates were selected according to the classification used by the enterprise, which may have aggregated various factors affecting *Salmonella* transmission or persistence into one variable. This classification, however, is made according to several requirements on standard biosecurity practices, and potential variations on these factors would be exceptions to the established requirement. Therefore, the covariates adopted in this study are effectively eligible to be changed by the enterprise, although some variables such as type and size of broiler houses may be more difficult to change than others like litter recycle.

Economic loss of having positively tested flocks should also be considered when setting strategies to reduce prevalence of the bacterium. If a flock tests positive for *Salmonella* spp. 2 weeks before slaughter, this flock will be processed differently at the slaughterhouse to reduce the risk of carcass contamination (25) and cannot be used to manufacture of products with more added value (processed products) but mostly directed to fresh or frozen products. This leads to revenue loss for the integrator as well as an increase in costs because *Salmonella* spp. positive flocks sometimes are held at the farm to be slaughtered at the end of the day to minimize risk of infecting negative flocks. Depending on the prevalence recorded for the integrator, flocks can be held even until one determined day (e.g., end of a given week), leading to significant increases in feed costs. Following the directives of the ministry of agriculture for the surveillance and control of *Salmonella*, based on World Organization for Animal Health [OIE] (49), every flock must be surveilled at least once before slaughter, and this information is further used for risk assessment by the veterinary authority. Therefore, data on *Salmonella* spp. occurrence is available for the integrator but may not be always stored in a way that allows effective data analysis, or is misused in terms of risk assessment.

With a proper system of data collection and an accurate model, it is possible to estimate the potential losses arising from *Salmonella* spp. contamination, unrelated to foodborne diseases. The detection on the pre-slaughter period and adoption of control measures markedly decreases this risk (25), but the costs of implementing different processing strategies, slaughter segregation, and restricted access to different markets have not been defined. To the author's best knowledge, there is no such a description in literature.

Using available cost information and estimated probabilities of detecting *Salmonella* spp. from litter related to litter recycles, we estimated how costs on replacing litter and its impact on producers profitability would incentivize producers working with type1 and type 3 broiler houses to use litter beyond the recommended number of recycles, which would lead to an increase in the odds of positive flocks. We also reported in **Table 7** the minimum expected net return per flock, calculated using the upper limit of probability of detecting *Salmonella* spp. related to litter use to allow for comparisons on the process of decision making under extreme risk aversion from producers (although we didn't formally account for risk in our analysis).

From a min-max selection criteria, considering that producers will choose to have the best possible performance in the worst case (50), the expected net return for all subsequent cycles after cycle number six is lower than the baseline scenario. This would discourage risk-averse producers to recycle litter with the objective of maximizing expected returns.

However, as this kind of extreme risk aversion does not always hold (51), it is possible that some producers would chose to maximize NPV, using the posterior median of expected returns as an estimate of payments, and ignore the issue of return variation. NPV analysis discounts a future stream of returns to compare decisions that may remain unchanged by decision makers for multiple rearing cycles. Under this decision rule, the problem faced by the producer is to choose between 12 consecutive payments equal to the baseline scenario, or 6 baseline consecutive payments followed by six variable payments according to each expected return.

This simple example highlights the importance of defining the risk factors related to *Salmonella* spp. occurrence and its respective cost share to allow effective control strategies and explains why producers may choose strategies that would lead to greater risk of *Salmonella* spp. occurrence. It is interesting to note that type 1 broiler houses were characterized in this study as riskier than types 2 and 3 with respect to *Salmonella* spp. isolation, and the economic incentive to recycle more litter may bring even more risk to the enterprise. Similarly, while type 3 broiler houses owners are incentivized to recycle more litter, this type of broiler house had the lowest probability of being contaminated with the bacterium.

The presented result is highly dependent on how the decision maker parametrizes the problem, in terms of assumption of decision rules (risk aversion), cost determination, cost share, and incentives. If the penalty applied for positive flocks is greater, the result will be different (in favor of adopting the proposed replacement scheme), as well as if instead of a penalty, a premium is paid for negative flocks, especially on the first six cycles period (aiming to reduce contamination or persistence of the bacterium), the risk for litter recycle on *Salmonella* spp. isolation may be reduced. These types of incentives clearly relate to an attempt to solve the principal-agent problem that is frequently described in agricultural cooperatives (52), as the producer and the enterprise manager may not share the same objective, which in this case is minimize *Salmonella* spp. occurrence. In this regard, there will be a conflict of interest between the enterprise (the principal) and the producer (the agent), in which the first maximizes profit by having the lowest possible rate of *Salmonella* spp. positive flocks, while the second has an incentive to maximize profit by reducing variable production costs, which may increase the rate of positive flocks. This may imply on a different optimal solution for the principal and the agent, creating the principal-agent problem. Although we didn't formally analyze the problem, specifying a function to be optimized by the principal, our study suggests that it is essential for the enterprise to establish clear contract terms to avoid asymmetric information and incentivize producers to adopt measures that will lead to a reduction on *Salmonella* spp. occurrence.

Our study is also important to shed light on the benefits for the enterprise of using official data linked to a systematic classification of broiler farms to identify risk factors related to occurrence of *Salmonella* spp., the importance of accurate cost determination and the use of incentives to induce producers adopting procedures related to the elimination of the bacterium. The advantages for the enterprise include understanding the probable causes of outbreaks and, given a more detailed follow up, the costs and benefits involved in prevention and control of the infection and the adoption of optimal control strategies.

CONCLUSIONS

This longitudinal study is the first Brazilian study using official data recorded from a broiler enterprise to establish risk factors related to farm characteristics and management strategies affecting the probability of isolating *Salmonella* spp. at the end of the grow-out period. We show evidence of spatial and time autocorrelation, which were accounted for by means of a Bayesian hierarchical model. Factors potentially related to the horizontal transmission of Salmonella, like type of broiler house, size of broiler house and total housing size significantly affected the probability of isolating the bacterium in litter. The number of litter recycles, likely related to the persistence of infection within broiler houses, also affected such probability.

We show how the risk for *Salmonella* spp. isolation increases as each of the risk factors change and we give an example where the producers will chose litter recycles strategies that will lead to increased probability of *Salmonella* spp. occurrence and discuss the role of establishing economic incentives to avoid the principal-agent problem and reduce the risk for positive flocks. Although the modeled scenarios may vary according to the cost and incentives adopted, it potentially shows an example of principal–agent problem and how it may impact *Salmonella* spp. persistence in the enterprise.

Future studies including more cycles and different covariates may clarify the dynamics of bacterial spread and allow for the establishment of optimal control strategies. Relationship of *Salmonella* spp. presence and production performance may also help clarify the effect of house size and farm capacity while allowing for a more accurate calculation of costs and returns for each evaluated farm.

Our study sheds light on the importance to use official data and systematic classification of farms and broiler houses to define risks for the isolation of *Salmonella* spp. using a reliable model specification. Extending data collection and using it to parameterize a diffusion model is a promising alternative for the enterprise to establish optimal control measures.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because the data sets generated for this study will not be made publicly available. Identification of farms and spatial locations are sensitive information from the enterprise and cannot be disclosed. Data on bacterial isolation may be disclosed upon request. Requests to access the datasets should be directed to pedrocm@okstate.edu.

ETHICS STATEMENT

Data on bacterial isolation from farms was provided by the enterprise and was collected as routine for official notification. Therefore, all data reported results from commercial broiler production, which is regulated by the Brazilian Ministry of Agriculture. Approval of an ethic committee is not required for the study type.

AUTHOR CONTRIBUTIONS

PM and CC contributed conception and design of the study. PM organized the database and performed the statistical analysis. PM wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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PERSPECTIVE
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Policy Perspectives of Dog-Mediated Rabies Control in Resource-Limited Countries: The Ethiopian Situation

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One Health disease-control programs are believed to be most effective when implemented within the population transmitting the disease. The World Health Organization (WHO) and partners have targeted the elimination of dog-mediated human rabies by 2030 primarily through mass dog vaccination. Mass vaccination, however, has been constrained by financial resource limitations. The current owner-charged dog vaccination strategy, used in most resource-limited countries like Ethiopia, has not reached the minimum coverage required to build population immunity. Dog vaccination is non-existing in most rural areas of Ethiopia, and coverage is <20% in urban areas. Although the health and economic benefits of rabies elimination outweigh the costs, the direct beneficiaries (public in general) and those who bear the costs (dog owners) are not necessarily the same. In this perspective paper, we aggregate evidence on the socioeconomic burden of rabies in Ethiopia as well as the implications for potential opportunities to control the disease and possibilities to obtain the required funding sources for evidence-based interventions in the control of rabies in Ethiopia.

Keywords: economics, Ethiopia, rabies, public health, health policy

INTRODUCTION

Rabies is among the oldest infectious diseases known to man, and it carries the highest case fatality rate (1). Every year, about 60,000 people die due to rabies, equaling 3.7 million disability-adjusted life years (DALYs). The disease additionally causes an economic loss of around 9 billion USD globally (2). All mammals are susceptible to rabies, and domestic dogs remain the primary source of the disease to other dogs, humans, livestock, and wildlife (3). An estimated 99% of human cases globally are due to a bite from a rabid dog (1).

Countries in the Americas and Europe have eliminated the disease in domestic dogs through vaccination. In resource-limited countries of Africa and Asia, efforts to control rabies have progressed over the past several years and have accelerated following the global initiative to eliminate dog-mediated human rabies by 2030 set by World Health Organization and partners (4). This initiative has also motivated additional funding from international and charitable organizations to support the rabies control efforts of governments, especially in resource-limited settings. In most parts of Africa, however, minimal action has been undertaken (1).

The Stepwise Approach toward Elimination (SARE) is an assessment tool developed through a joint effort of the Food and Agriculture Organization (FAO) of the United Nations and the Global Alliance for Rabies Control (GARC) to provide a standard mechanism for countries to assess their current rabies control efforts and to measure progress in eliminating dog mediated human rabies. Ethiopia appears to be at an early stage (5). The SARE assessment identified several critical gaps including a lack of quantitative evidence on the burden and poor inter-sectoral collaboration between public health, animal health, and wildlife authorities. Following the first SARE assessment in 2016, the country established a One Health Working Group in the country with representatives from public health, animal health, and wildlife authorities, along with CDC, FAO, and Ohio State University; this included a Rabies Technical Working Group that developed a national rabies control and elimination strategy for the country (6). Although regions like Addis Ababa already mandate rabies vaccination requirements in place, in all administrative regions, canine vaccination is voluntarily-based and owner charged. Vaccination coverage varies from 18% in urban areas to almost non-existent in rural areas. These coverages are far lower than the 70% recommended minimum coverage to prevent rabies outbreaks (7). Although mass vaccination of dogs is a proven and cost-effective means of rabies control, there is a lack of motivation from owners and an inadequate intervention from local governments due to a lack of political will and resources (8).

Public and animal health authorities use disease burden metrics to set priorities in health investments (9). Often, these metrics do not consider all aspects of the socioeconomic burden of the disease. For instance, most of the burden studies focus on a human health perspective, and there is a paucity of data available on the health and economic impacts of rabies on livestock, wildlife, and animal welfare. Part of the problem is the lack of recorded and reported health data at human and veterinary health centers.

In this article, we summarize results from studies generated from registered rabies exposure and death cases of humans as well as from estimates using innovative data collection methods including contact tracing and participatory approaches to obtain the best possible estimate of the health and economic impact of rabies in humans and livestock in Ethiopia. Thus, the objective of this article is three-fold, (1) to summarize the burden of rabies in Ethiopia, (2) to indicate the potential benefit of vaccination control practices, and (3) to detail potential mechanisms to fund dog vaccination campaigns in resource-poor countries like Ethiopia.

HEALTH AND ECONOMIC BURDEN OF RABIES

Registered rabies cases, both by veterinary and human authorities, are underreported in many African and Asian countries. Consequently, officially registered data on rabies underestimates the true burden of the disease (10–13). In Ethiopia, no official mechanisms exist for public reporting of dog bites or rabies-related deaths unless people report while seeking medical treatment in health centers. In rural areas, the preferential use of traditional/spiritual healers might also contribute to the reduced level of post-exposure prophylaxis (PEP) (14). Based on registered health records, the annual human rabies exposure rate (based on refined exposure risk assessment performed following rabies suspected animal bite) per 100,000 population has been estimated to range from zero to 40 (15, 16). To account for underreporting, Beyene et al. (17) conducted an extensive survey-based case search, also known as contact tracing. The contact-tracing method has been demonstrated to give access to unregistered rabies exposures where exposure and or death cases are not fully registered (18, 19). Beyene et al. used registered cases obtained from health centers as a starting point to search for unregistered exposure cases in three representative districts. Results indicated that about 23% of the exposure cases (bitten by potentially rabid animal) did not seek medical attention. Accordingly, the annual suspected rabid dog exposures, which was based on the six criteria for rabies diagnosis in living dogs (20), were estimated to be 135, 101, and 86, resulting in 1, 4, and 3 deaths per 100,000 population within the studied urban, rural highland, and rural lowland districts, respectively. A treatment was assumed to be sufficient, adherence, only if the individual received the minimum recommended doses (at least 14 out of the 17 doses) of nervous tissue made PEP. Extrapolation of the district results to the national level using data from the country's national statistics on human population distribution in urban and rural districts as well as probabilities of disabilities and or deaths across ages indicated an annual estimate of ∼3,000 human deaths resulting in about 194,000 DALYs per year as well as 97,000 exposed persons requiring on average 2 million USD treatment costs per year countrywide (1, 17). Twenty three percent of total human exposure cases included in the study were unreported and identified through the contact tracing. These findings suggest that relying on self-presentation for medical treatment will fail to reach ∼1/4 of exposure cases. Communities should be encouraged to report dog bites, and active investigation of all known bites by appropriate authorities would be expected to identify additional exposures that require treatment, thereby saving lives. In 2001, WHO issued a resolution for the complete replacement of nerve tissue vaccines with cell-culture rabies vaccines. However, sheep brain-derived rabies vaccine is still being manufactured and used for most exposed patients in Ethiopia. This rabies vaccination has shown to cause disabilities and associated with costly indirect expenses as it requires up to 17 doses to complete full dose (17). Current initiatives of the Ethiopian government to invest in upgrading the facilities required to produce a safer and effective cell culture-based anti-rabies vaccine in line with WHO recommendation has to be encouraged (21).

Governments often use Disability-Adjusted Life Years (DALY) or Quality-Adjusted Life Years (QALY) estimations to rank diseases and to set priorities for health investments (22). Global funds also often prioritize public health-related grants following the DALY/QALY approach (23). Although rabies has a case fatality rate of nearly 100%, it is not on the top list of 25 most common diseases in countries like Ethiopia where diseases like malaria with a higher DALY/QALY burden prevails (24). However, the burden of zoonotic diseases such as rabies encompasses not only DALYs but also productivity/income losses, treatment-related costs, and societal costs in terms of psychological and emotional anxiety. The impacts are magnified in areas with poor access to PEP and in impoverished and remote rural communities. Rarely considered are the effects on livestock production threatened or endangered wildlife species (2, 23).

For the majority of Ethiopians, livestock is a direct source of livelihood, in terms of food and income. While crop output represented 32% of the country's GDP, about 80% of Ethiopian farmers use animal traction to plow their crop fields (24–26), and their crop production is affected when their oxen are diseased and lost due to rabies. Rabies outbreaks among the endangered Ethiopian wolf have nearly driven them to extinction (27). As such, the use of only DALY/QALY measure or the human health burden to set priorities in health investments is not serving the overall societal interest in the best way; a broader approach accounting for a more holistic assessment of the rabies burden is necessary.

ECONOMIC BURDEN IN THE ETHIOPIAN LIVESTOCK SECTOR

In Ethiopia, estimates on the burden of rabies in livestock are almost non-existent, except sporadic case reports (11, 12, 27). A recent attempt to evaluate the burden of rabies in cattle using a systematic approach was conducted in two systems of subsistence livestock farming systems, using a participatory approach. In this study, cattle rabies incidence rates at herd level were 21 and 11% for the mixed crop livestock and pastoral production systems, respectively. The incidence rate at cattle level was the same 2% in both systems. The annual national loss due to rabies in cattle alone was estimated to be 210 million USD per year (28). This is consistent with an economic model that predicted the financial loss to be between 10 and 412 million USD per year (2). The economic burden of rabies in cattle is not evenly distributed; it is especially severe for farmers in pastoral production systems who rely on cattle for much of their livelihoods (29).

BURDEN ON WILDLIFE CONSERVATION, RESEARCH, AND TOURISM

Rabies threatens many of the endangered species of wildlife. The Ethiopian wolf is one of these species whose number is decreasing at an alarming rate due to rabies and other viral diseases (30). Although scarce literature documented the contribution of wildlife to the Ethiopian economy, wildlife-based tourism contributes significantly to the economy of Kenya, Tanzania, and Uganda (31–33). As populations decline to make them more difficult to locate, research, and wildlife-centered tourism could decrease. Additionally, tourism in general may be reduced due to fears of contacting a rabid dog.

IMPLICATIONS ON THE ECONOMICS OF CONTROL

Nearly all cases of rabies in Ethiopia originate from dogs. Many countries have demonstrated that canine mass vaccination will reduce the burden of rabies in humans as well as in livestock and wildlife (2, 30, 34). Reducing disease also improves animal welfare. The cost-effectiveness for dog vaccination has been demonstrated in various countries of Africa and Asia (29, 31). Specific parameters like dog population and livestock density affect cost-effective vaccination coverage. A global needs assessment study estimated dog population in Ethiopia to be 11.7 million using extrapolation of dog per human population data (35).

In Ethiopia, Beyene et al. (8) estimated the cost-effectiveness of mass vaccination in representative urban and rural districts while accounting for human health impacts as well as livestock impacts. This particular study simulated over the period of 5 years identified vaccination coverages of 70 and 80% to be the most likely to provide the greatest net health benefits in urban and rural districts, respectively. The exclusion of cattle related losses in the cost-effectiveness analysis, for the rural district scenario, shifted the cost-effective coverage from 80 to 50%, suggesting that the economic burden of rabies in cattle represents a relevant financial incentive for canine vaccination. Based on a more inclusive notion of disease burden, the cost-effectiveness analysis for the rural district showed that all tested vaccination scenarios varying from 10 to 90% coverage resulted in a positive net monetary benefit. In other words, the cost of the mass vaccination campaign is less than the total financial loss associated with rabies, which includes cattle-related rabies. On the other hand, the active investigation to identify other bite victims also comes at an reasonable additional cost to the program, which was not included in the cost accounting of the study (8). Similar studies need to consider at least costs of risk-based investigation, although implementation has been difficult for many countries including Ethiopia where funding for dog vaccination is limited.

In this study, elimination would not be achieved within the first 5 years but the level of coverages would protect an outbreak and sporadic rabies could occur. Consistent and higher coverage would be required to eliminate rabies virus transmission and low coverages would not eliminate the disease in the dog population that requires sustained vaccination costs indefinitely. The net benefit could be even higher if tourism losses secondary to rabies fears as well as conservation of wildlife could be included in the analysis.

WHO SHOULD PAY FOR DOG VACCINATION?

For an annual cost-effective canine mass vaccination campaign with a coverage of 70% in urban and 80% in rural, the total investment for Ethiopia is estimated to be 17.5 million USD/year, in the order of 0.2$/dog per year (8). An investment of 17.5 million USD is a big investment for the Ethiopian government to allocate to rabies control compared to the amount of the budget allocated to the health sector in general. A comparable estimate has been reported by the team of researchers from CDC, WHO, and FAO on needs assessment and Alternatives for Progress Based on Dog Vaccination to meet the 2030 target of dog-mediated human rabies elimination for Ethiopia to be $135 million for a period of 2017 to 2030 (35). The Ethiopian government allocated about 7–11% of the total fiscal budget to the health sector, which equals 388 million USD (36). Though the Ethiopian government determined that rabies was a top-priority zoonotic disease in 2015 (37), sufficient funding to conduct an 17.5 million mass vaccination campaign have not been allocated to accomplish this goal. On the other hand, the budget estimate assumes that every community in Ethiopia requires dog vaccination. This might be an overestimate as there could be communities that would not require vaccination due to the very low risk of transmission perspective pertaining to the lower population density of dogs as demonstrated by a study conducted in Uganda (38). Similar studies that could identify areas with their potential risk of rabies would be helpful for budget allocation purposes. Utilizing external resources like international partners, including CDC and Ohio State University, which provide training for staff to plan and conduct mass vaccination campaigns and cover part of vaccination cost, could help; however, consistent funding is needed for desirable outcome (39).

Even though the benefits of rabies elimination outweigh the costs of control, the beneficiaries (general public and livestock owners) and those who bear the costs (dog owners) are not necessarily the same. The benefits in terms of improved public health, reduced costs of post-exposure treatments, and better cattle health are not distributed to the public equally. Given the current situation in Ethiopia, insisting on owner-charged dog vaccination is expected to result in far lower coverage. This is supported by a review article of the literature on mass vaccination in Africa which found that none of the fee required projects reached the 70% target vaccination coverage, while the free campaigns consistently achieved higher vaccination rates (40). The challenges in urban districts are exacerbated by the presence of free-roaming dogs (owned and/or without owners) compared to rural areas, which are less likely to be vaccinated in owner-fee campaigns (41). Effective rabies vaccination of dogs would require government involvement in covering the associated costs. A partial dog–owner contribution could also be applied as demonstrated in Asia (42).

Governments could follow financing strategies such as joint financing including the "separable costs–remaining benefits" method of cost-sharing (43) to allocate the expenditures to both sectors proportional to the benefits gained by both sectors, for instance, veterinary, and public health sectors. Such a proportional allocation of resources was also simulated for Rift Valley Fever control in Kenya and Brucellosis control in Mongolia (37, 38). A more sustainable rabies control program was demonstrated in Bohol (Indonesia) through legalizing the control framework (i.e., compulsory dog registration to establish responsible pet ownership and accountability in combination with mass vaccination to establish dog herd immunity), mobilizing local resources and involving the local community (44). Alternatively, synergistic funding options for vaccination campaigns could include a loan through development-impact funding, where investments are paid back over several years once savings are noticed as a result of benefits from disease control (45). Potential savings result from a reduced need for post-exposure prophylaxis and wound treatments and other related healthcare facility resource expenses. This approach is a form of social impact bond, whereby initial costs of disease control are supported by private investors and repaid by donors and governments once agreed outcomes are achieved. These funding mechanisms were demonstrated to work for the control of sleeping sickness in Uganda (46). Given that rabies has a readily available vaccine that is highly effective, and it requires a relatively large public investment, rabies control would be a perfect candidate for such financing in countries like Ethiopia. Effective control of rabies would likely reduce human incidence leading to a significant reduction in PEP, which is currently an expenditure to the government (47). Although there would not be a direct monetary saving for the government as a result of the saving from reduced burden of the diseases in livestock, it provides an indirect societal benefit in times of food insecurity. Short-term saving for the government would be from reduced expenditures related to PEP production and or import could be used to pay back the bonds.

To better prepare the country to conduct mass vaccination of dogs, various partners including Global Health initiative at Ohio State University and CDC have been building capacity and, through multiple training efforts, have increased vaccination coverages in some localities. Collaboration between public and animal health authorities in terms of sharing expertise and resources should be developed. Establishment of such units at different administrative levels, including practicing veterinarians and medical doctors, would improve communication about specific risks and could contribute to practical One-Health-oriented cooperation. Such collaboration between human and animal healthcare professionals can also avoid unnecessary public expenditure due to post-exposure treatment in the case that biting dogs are investigated and found not to be rabid. Active investigation of all dog bites can lead to the identification and treatment of other persons who were exposed as well as verify the rabies status of the animal. Operationalizing such a cross-sectoral agenda could be challenging in most countries (48). However, some countries, Kenya and Haiti, for instance, have successfully established a zoonotic disease unit and implemented (48, 49). Apart from rabies, in Ethiopia, some of the top-listed diseases in terms of health burden like diarrheal diseases are partly zoonotic (22), indicating a broader benefit for operationalizing a One Health approach.

CONCLUSION

In this perspective article, we demonstrated that through uncovering evidence on the multifaceted burdens of rabies using unconventional methods; it is possible to generate evidence that contributes support toward a cross-sectoral political and financial approach to canine mass vaccination. Particularly, in rural livestock-owning communities, the impact of rabies on cattle health and productivity, in addition to its public health impacts, could be viewed as an additional incentive for governmental support of canine vaccination efforts. Rabies has already been declared by the Ethiopian government to be a priority zoonotic disease. Considering a broader definition of the evaluation of disease burden could also help justify the funds needed for rabies effective control. Most of these are also consistent with findings from global and regional rabies burden estimation models.

Despite availability of Ethiopian and global evidence on rabies burden and cost-effective options, little improvements have been made on practical interventions of rabies by the Ethiopian government over the past years. While the authors recognize the financial challenge to implement intervention, the country needs to further explore a way to operationalize the principles of One Health involving various sectors. In addition, we strongly believe that (1) it is not reasonable for dog owners to shoulder the majority of the cost for rabies vaccination efforts aimed to protect the entire population, (2) when primary vaccination efforts rely on dog owners to pay for rabies vaccination, even if they could all afford it, vaccination coverage rates high enough to interrupt dog-to-dog transmission of rabies will not be achieved; it is recommended that mass rabies vaccination of canines be conducted through free or partial cost to owner programs that target both owned and free-roaming dogs. Furthermore, One Health collaboration in other areas including dog bite investigation and public awareness should be considered to control rabies.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

TB, MM, and HH conceived the idea and organized the literature review. TB analyzed the data and interpreted the results. TB, MM, HH, JO'Q, SL, and JB wrote the draft of the manuscript and completed the final version for submission. All authors approved the final version of the manuscript before submission.

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Consumer Reactions to *E. Coli* and Antibiotic Residue Recalls: Utility Maximization vs. Regret Minimization

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Food safety remains a major issue to many consumers. Previous studies examining the economic impact of food safety recalls have focused on Class I recalls. Antibiotic residue in meat products, a Class II recall, has increased in consumer importance yet little is known about how much research and development expenditure should be allocated to reduce antibiotic residue pre- and post-harvest. This study compares demand elasticities and the decrease in willingness to pay in response to either an *E. coli* (Class I) or antibiotic residue (Class II) recall. We compare and contrast two competing behavioral frameworks, Random Utility and Regret Minimizing. Modeling behavior using the random regret framework is found to be more powerful for assessing consumer responses. In addition, we explore if different groups of consumers exist that either maximize utility or minimize regret. Consumer devaluations of *E. coli* (Class I) are 40–65% larger than antibiotic residue (Class II). Approximately 60% of consumers are identified as regret minimizers and 40% were identified as utility maximizers. While industry response and government policy recommendations differed conditional on modeling framework, the regret minimizing framework required smaller price discounts than regret minimizing to maintain the same level of market share.

Keywords: antibiotic residue, *E. coli*, food recall, discrete choice analysis, random regret minimization, random utility maximization

INTRODUCTION

Consumers trust government regulatory agencies to ensure food products are safe to eat and to publicize product recall notifications when food safety breaches occur. Potential long-term economic losses along the food supply chain due to food safety events are particularly concerning given potential loss of consumer confidence. Furthermore, recalls can endure for several months, as product hazards can take time to identify and trace. By the time that these tasks have been completed, many products already have been shipped and sold to consumers and may never be recovered via a food recall[1]. Several studies have estimated economic impacts of meat product food safety recalls, including losses accrued by upstream and downstream market participants (2), livestock market reactions (3), and retail meat demand impacts (4).

[1] For example, in the 1998 Colorado Boxed Beef *E. coli* recall, of 359,000 pounds of ground beef implicated in the recall, only one pound was ultimately recovered (1).

The magnitude of economic losses associated with food recalls has incentivized pre- and post-harvest research, development, and regulation to mitigate impacts. A key question that arises is: What is the optimal amount of investment to reduce future food safety issues? For example, to reduce the occurrence of pathogens in meat products, Hazard Analysis and Critical Control Point (HACCP) regulations were enacted in the United States in 1996. Antle [(5). p. 321] estimated that the annual costs of these regulations "could range from about $500 million to $5 billion (1995 dollars)." Knowing how much consumers devalue products as a result of a food safety breach can help inform the value of improving food safety. However, consumer valuations may differ by the cause and circumstances surrounding food safety recalls.

One way to classify food safety breaches is by their probability and potential severity to human health. Using this method of classification, the United States Department of Agriculture's Food Safety and Inspection Service (USDA-FSIS), which is responsible for inspections and recall notifications for meat, poultry, and egg products, classifies food recalls into three broad classes. Class I (Class II) recalls imply that the potential issue has a reasonable (remote) probability that eating the food will cause human health problems or death, whereas a Class III recall involves a situation in which eating the food will not adversely affect human health. With few exceptions, literature examining the impact of food safety issues has focused on the more frequent and costly Class I recalls such as *E. coli*, Listeria, and Salmonella. Little is known about how consumers react to Class II recalls, which are fewer and tend to have less immediate acute health outcomes.

This research estimates the magnitude of consumer devaluation by food safety class Specifically, we compare consumer valuations for ground beef given either an *E. coli* (Class I) or antibiotic residue (Class II) recall, conditional on the type of retail outlet involved in the recall. From this, we derive consumer willingness to pay for additional private non-government food safety testing. We then empirically test the factors believed to influence consumer ground beef valuation including consumer shopping behavior (6–8), household cooking arrangement (8), organizational trust for food safety information (9), and purchase regret when health can be affected (10, 11).

We focus on *E. coli* and antibiotic residue for several reasons. Antimicrobial residue is an FSIS Class II consumer food safety concern that has recently received considerable public attention. Concerns have centered around allergies to antimicrobial residues, maximum allowable residue levels, and perceived threats to public health through antimicrobial resistance (12). While the number of meat products testing positive for antibiotic residue is low[2], little is known about how much consumers devalue meat products given an antimicrobial residue recall. *E. coli* is a frequent FSIS Class I consumer food safety concern that has received considerable research and public attention and thus provides an appropriate food safety recall for comparison.

Previous studies examining impacts of food safety recalls due to *E. coli* have used identification strategies that leveraged recall frequency and magnitude. In contrast, only three antibiotic residue FSIS recalls have been issued in the last 5 years, each with relatively small meat volumes recalled. In such situations with infrequent occurrence and small magnitudes, traditional identification fails because of few non-zero values and larger variation. One alternative method, which we use here, is to develop a hypothetical choice experiment to allow for identification and comparison of consumer devaluations given choice attributes. This choice experiment asked a representative sample of U.S. consumers to make repeated choices between three shopping scenarios. Consumers were asked to select the shopping scenario where they would purchase ground beef. Shopping scenario attributes included a potential food safety recall in the previous month (*E. coli* or antibiotic residue), store location (supermarket, club, and convenience), additional private testing, and the price of ground beef. Ground beef valuations and elasticities were derived from estimations which observed consumer purchase decisions across multiple choice sets.

Utility maximization is the behavioral decision rule most often used to obtain consumer valuations, and in particular, in choice experiments involving food purchasing decisions. This rule assumes that consumers evaluate the set of shopping scenarios and then select the one offering the most utility or satisfaction. Despite the popularity of utility maximization, consumers making risky choices where they face (potentially) short or long-term sub-optimal decisions may be subject to regret. One recent alternative framework allows regret to be incorporated as a behavioral decision rule—assuming consumers aim to minimize regret (13). Incorporating regret allows the chosen alternative to depend on the anticipated performance of non-chosen alternatives. This behavioral variation has received increasing attention in transportation, urban planning, environmental economics, and health economics, and when significant potential losses, gains, or policy implications are involved, as is the case with food safety [e.g., (14–20)]. These studies assessed circumstances under which random regret minimization is a more appropriate behavioral assumption than utility maximization. We add to this literature by comparing the relative performance of the Random Utility Model (RUM) and Random Regret Minimization (RRM) under risky decision making in the context of food safety recalls.

We find that 60% of consumers in our sample are better modeled using a regret minimizing framework as opposed to utility maximization. This suggests, in the case of food safety valuation, studies assuming utility maximization might be misclassified and hence lead to incorrect policy recommendations. Our results add to the literature examining differences between random regret and utility maximizing behavioral frameworks by focusing on the context of decisions where there are potential short- and long-run negative impacts on human health. Our work confirms previous findings that a regret minimizing framework may be more appropriate in circumstances where there are actual losses or gains (20). We

[2]Processed meat is subject to both random and targeted sampling for antimicrobial residue by FSIS's National Residue Program. While the number of samples violating residue levels remains low (∼0.3% for livestock products) some products inevitably pass inspection, reach the supermarket and are later recalled due to consumer reports of adverse reactions or illnesses from product consumption.

show that the RRM is the statistically preferred model that generates lower willingness-to-pay estimates and more elastic attribute estimates. Using price as a policy mechanism implies lower price discounts are required to maintain a given level of market share compared to the RUM framework.

The rest of the paper is organized as follows. Section food safety detection, frequency, and impact describes the process of potential food safety issues, frequency and type of recalls, and previous results on the economic impacts of recalls across food safety classes. Section data describes the data and the hypothetical choice experiment used. Section methods presents two simple models to frame consumer choice under two different behavioral assumptions. Section results presents empirical results and simulates potential industry and policy responses. Section discussion and conclusions concludes the article.

FOOD SAFETY DETECTION, FREQUENCY, AND IMPACT

Process of Food Safety Detection

The primary objective of a food safety recall is to reduce human health hazards by removing potentially harmful, contaminated, or mislabeled products from the market. Information about products that have been recalled is provided by the U.S. Department of Health and Human Services Food and Drug Administration (FDA) and by USDA-FSIS. The FSIS is responsible for inspecting and regulating meat, poultry and processed egg products produced in Federally inspected plants. All remaining food products are regulated by the FDA.

FSIS works to address potential meat, poultry, and egg safety issues through a five-step process: problem identification, preliminary investigation, recall deliberations, notifications and actions, and recall closure. FSIS identifies potential food safety issues through regular sampling, consumer complaints, epidemiological or laboratory data submitted by public health departments, company self-reporting, and other government agencies. Based on this information, a preliminary investigation can be conducted which includes gathering additional product information and potentially harmed individuals. The objective is to determine whether the alleged product caused, or has the potential to cause, negative health outcomes. With this additional information and analysis in hand, FSIS determines if additional action is warranted. Potential actions include product recall, public health alert, regulatory action, or no action. If a product recall is issued, the recall is classified into one of three safety classes based on relative risk to human health, and the responsible firm is contacted with a request to voluntary recall products.

If the firm agrees to a voluntary recall of potentially harmful products, FSIS notifies the public. The classification of the food safety issue as a human health hazard determines the medium by which FSIS notifies the consumers. A Recall Release is used for Class I and Class II recalls and a Recall Notification Report for Class III recalls. The primary difference between the Recall Notification Report and Recall Release is that the Recall Release is disseminated to public health partners. Regardless of recall classification, all public releases are publicly posted. After public notification of the food safety issue, FSIS works with firms to ensure that they are making reasonable and timely efforts to notify and work with product distributors to remove potentially contaminated products. When a reasonable effort has been made to contact and retrieve potentially contaminated products, FSIS removes the food safety issues from current monitored recalls, and no additional testing or monitoring occurs.

Type and Frequency of Food Recalls

Food recalls are categorized into one of three classes by their probability to cause human health problems or death. Class I (Class II) implies that there is a reasonable (remote) probability that eating the food will cause human health problems or death whereas Class III recall involves a situation in which eating the food will not adversely affect human health. Examples of a Class I recall includes the presence of Shiga toxin-producing *E. coli* (STECs) in raw ground beef. Class II recall examples include the presence of very small amounts of undeclared allergens associated with milder human reactions (e.g., wheat) or antibiotic residue. Class III recall examples include the presence of non-allergenic products such as excess water in meat products. Thus, recall classes can span across multiple species and processed product formats.

The far-left chart in **Figure 1** displays the number of recalls annually by FSIS safety class. Class I recalls have sharply increased since 2010, whereas Class II and III recalls gradually increased until 2010 but have since leveled off. The distribution of causes for recalls has changed through time. For example, recalls due to *E. coli* contamination were the most common in 2007 but declined year-over-year until 2013 and then stayed constant between 2013 and 2018 (middle chart, **Figure 1**). Allergens or foreign material recalls were less common in 2005 but sharply increased as the primary reason for food recalls. Although most food issues can span across multiple species and processed product formats, there does not appear to be any difference in frequency across food issues within a given species (far right chart **Figure 1**). The exception to this is the larger number of beef food safety recalls between 2006 and 2010 compared to other meat and poultry products.

Impact of Food Recalls

The economic impacts of food safety recalls have been explored extensively. Studies have examined the impact of food safety recalls on company stock prices (21–24), retail meat and livestock prices (2, 3, 25–27), and meat demand (4, 28–30). The impact of recalls is known to have both short- (4) and long-run (31) implications within the species for which the recall occurred and spillover effects into other species. Some studies have focused on the impact of high-volume beef recalls due to *E. coli* [see Moon and Tonsor (2) for a recent example] compared to low occurring Hepatitis A (23) or Bovine Spongiform Encephalopathy (BSE) (26).

Other studies have focused on how mitigating the impacts of food safety recalls affects downstream and upstream participants. Tonsor and Schroeder (32) examined the impacts of adoption of an *E. coli* vaccine at U.S. feedlots. They concluded that feedlots were unlikely to adopt such a vaccine unless compensated to offset the direct costs of adoption. Moon and Tonsor (2) examined price reactions along the beef-cattle supply chain due

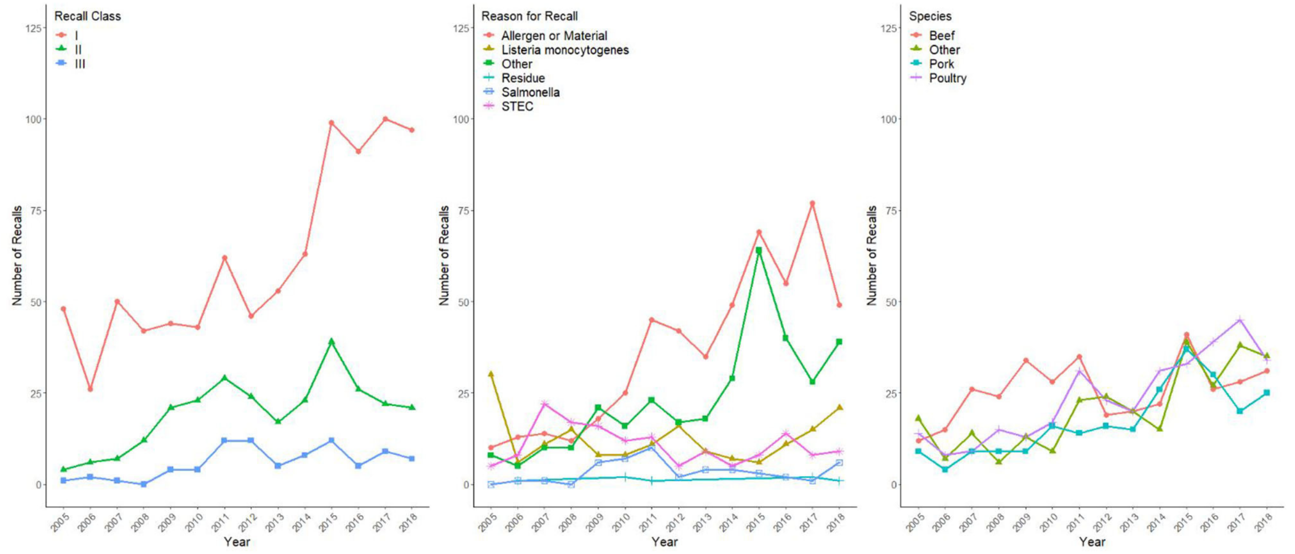


FIGURE 1 | Number of food safety recalls by class, reason, and species (USDA-FSIS 2020).

to an official *E. coli* beef safety recall. Local downstream agents were more likely to be affected financially from an official *E. coli* beef safety recall compared to livestock producers. Thus, implementation of additional risk abatement efforts by local downstream agents, above current practices, were likely to be financially beneficial. Tonsor et al. (9) examined how product characteristics affected consumer perceptions of food safety issues and how trustworthy information sources were viewed. Consumers who placed considerable trust in product credence attributes or in information obtained from health professionals perceived low levels of beef safety risk. Thus, product attributes and information sources can partially mitigate the effects of a food safety recall.

A common thread in past studies is their focus on Class I food safety issues (i.e., where there is a reasonable risk of human health problems or death). This class of recalls tends to be large in volume, more frequent, and highly publicized where human health issues are immediately noticeable (see **Figure 1** left chart)[3]. Little work has focused on the impact of Class II food safety recalls, which pose minimal risk to human health. This class of recalls tends to be small in volume, less frequent, and less publicized, even though the subjects of such recalls can potentially affect the long-term health of affected individuals (see **Figure 1** left chart). Infrequent occurrence and wide variation in volume in some Class II recalls could lead to biased estimates using commonly used econometric identification strategies.

One way to deal with the issues of recall class heterogeneity is to focus on building demand indices that span across multiple food safety classes (31). Such "food safety indices" do not directly capture the impact by class heterogeneity but rather provide an average or weighted average impact across all classes. If consumer valuations for food safety recalls are a function of the relative probability of illness and death, then the magnitude of impacts should be different across classes. Thus, consumer reactions to and valuations of Class I recalls should be larger in magnitude than those of Class II recalls, and Class II recalls larger than Class III recalls. Likewise, the valuation of Class III recalls should be ∼0, given that this class of recalls does not pose any probability of human health problems or death. The relative difference in magnitude between Class I and Class II recalls is uncertain and likely to vary given the food safety issues compared.

It seems obvious that food safety events lower retail prices, since there is a loss of consumer confidence (4) resulting in lower expected utility from consumption and reduced demand. However, no studies have attempted to compare consumer valuations across food safety classes. This study compares one Class I food safety recall (*E. coli*) and one Class II food safety recall (antibiotic residue) in order to understand better consumer perceptions across food safety classes.

DATA

Sample

The primary objective of this study was addressed by conducting a nationwide online survey of meat-eating shoppers. The survey was developed and pretested by 120 respondents, the majority of whom resided in Kansas. The pretest identified potential issues regarding survey length, questions, and responses. The final survey was then delivered to an online panel of consumers provided by Survey Sampling International (SSI) in the summer of 2017. SSI maintains a list of individuals who "opt-in" to receive and potentially participate in online surveys.

[3]The frequent media links between Chipotle Mexican Grill and *E. coli* in 2015 caused sharp decrease in restaurant patronage reflected in stock price devaluation. The incubation period for *E. coli* is usually 3–4 days after the exposure, but may be as short as 1 day or as long as 10 days. Symptoms begin with a mild belly pain or non-bloody diarrhea which worsens over several days.

Individuals who received the survey from SSI "opted-in" to complete the survey and respondents who subsequently completed the survey received $4.00 (2017 dollars) from the researchers. Individuals who did not "opt-in" to the survey or exited prior to completion did not receive any monetary compensation. Since our focus was on the individual's valuation of meat products due to a food safety issue, we discarded respondents who did not eat meat[4]. On average, individuals took 25.8 min to complete the survey. In total, 2,696 individuals entered the survey, 2,640 agreed to the associated survey risks, 2,065 completed the survey, of whom 1,994 respondents ate meat. Thus, 1,994 responses were obtained and subsequently analyzed.

Demographic information from the 2010 U.S. Census (33) were used during survey sampling to ensure that survey respondents were representative of U.S. consumers. **Table A1** compares survey respondent demographics to 2010 Census values. Survey respondents were slightly more educated, with a higher representation of female participants, and had slightly less income on average. Other demographic characteristics of the sample closely aligned with the 2010 Census. The sample of respondents through SSI may not represent a completely probabilistic sample of the population, which may result in a somewhat less representative sample, given respondents "opt-in" to take the survey. A benefit though is that the results may be more accurate for respondents that opted in, given their potential interest in the survey topic (34).

The survey included questions regarding meat consumption habits, food shopping, and cooking and meal preparation behavior, as well as the usefulness of various organizations for food safety information. Individuals were asked to specify how often they eat a specific meat product using the categories of (i) never, (ii) once a month or less, (iii) two to three times per month, (iv) once per week, and (v) more than once a week. **Table A2** summarizes the frequency of meat consumption by meat product. Chicken and beef were the most frequently consumed products. Approximately 57% (45%) of respondents ate chicken (beef) at least once a week. Fish and turkey were the least commonly consumed meat products. Approximately 44% (55%) of individuals ate fish (turkey) once a month or less or not at all.

Individuals were asked what their role was in shopping, the store format where the majority of shopping took place, and their role in cooking. **Table A3** summarizes responses to these questions. Across all store formats, ∼59% (38.20 + 17.69 + 2.75 = 58.64) of respondents indicated that they did all the food shopping, 26% did the majority of their food shopping, 8% divided food shopping responsibilities, and 8% did the minority of shopping for their household. When choosing a store to purchase food from, ∼65% of individuals indicated that they purchased the majority of their food at supermarkets, 30% primarily purchased at club stores, and 5% purchased at "other" stores[5].

Approximately 61% (40.61 + 18.15 + 2.5 = 61.26) of individuals indicated that they cooked food themselves, 28% cooked together with another household member, and 11% indicated someone else was primarily responsible for cooking. Additional combinations of cooking and shopping habits by store format can be explored using **Table A3**. For example, ∼32% of respondents did all the food shopping, primarily at a supermarket, and were responsible for all of the cooking.

Food safety information sources are known to affect consumer food safety perceptions significantly (9). Respondents were asked to classify 27 information sources as either "helpful," "somewhat helpful," or "not helpful" for receiving food safety information. The 27 information sources were allocated into six broad parent groups: government, advocacy groups, producer, store, media, and family and friends[6]. Descriptive statistics are summarized in **Table A4**. Government and family and friends were viewed as the two most helpful sources of information. Food safety information from the government (family and friends) was considered "helpful" or "somewhat helpful" 58.4% (57.5%). Advocacy groups and stores were viewed as the least helpful for food safety information.

Stated Choice Experiment

Hypothetical stated choice experiments are a subset of stated choice experiment methods where individuals select what they would do in a hypothetical situation but are not required to take physical action. This methodological subsection is particularly useful when a product or event is infrequently or not observed. These methods have been widely applied in studies of psychology and social behavior (35, 36), public health (37, 38), economics (39, 40), marketing (41, 42), environmental valuation (11), and transportation (43, 44).

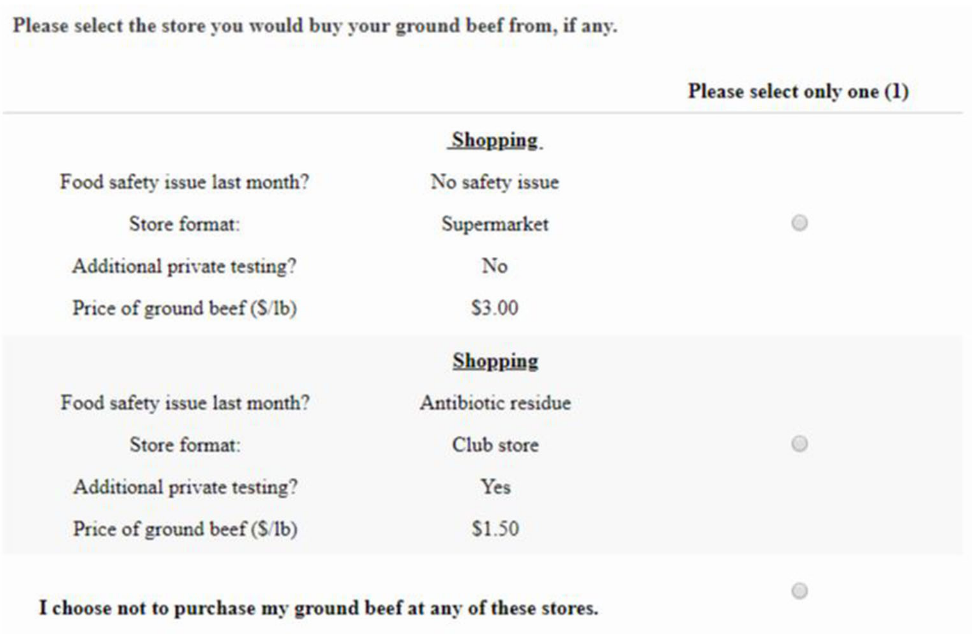
A hypothetical stated choice experiment (CE) was created to estimate shopping scenario elasticities and consumer WTP for one pound of ground beef given a hypothetical food safety recall. One concern when using hypothetical stated choice experiments is "hypothetical bias," the difference between reported/stated and actual action. "Cheap talk" scripts ask individuals to imagine themselves in the situation prior to making a purchase decision and have been shown to reduce hypothetical bias (45). Thus, a cheap talk script was included in the survey prior to stated choice question[7]. Each individual was asked to consider six

[4]People who self-identified as not eating meat completed the survey is significantly less times (18.5 min) than those who self-identified as meat eaters (25.8 min). This provides some evidence that individuals who did not eat meat products were less engaged in the survey, thus potentially downward biasing the results.

[5]"Other" stores include dollar stores, drug stores, natural + organic stores, convenience stores, ethnic food stores, and online-only food stores.

[6]Government included FSIS, FDA, CDC, and food industry scientists. Advocacy groups included consumer organizations and environmental groups. Producers included food manufactures, farmers/growers, and local butcher. Stores included my primary food store, fine dining restaurant, casual dining restaurant, and fast food restaurant. Media included TV, radio, newspapers, food magazines, food and cooking channels, social media, blogs, internet website, and entertainment industry. Family and Friends included friends, family, doctors, and health/dietary/life coach.

[7]The cheap talk stated the following "*Imagine you are thinking about going to a store to buy ground beef. Each store will have the following: a specific format (e.g., supermarket or club store) whether a food safety issue has ever occurred in the store (E. coli or antibiotic residue) whether additional private ground beef safety*



Please select the store you would buy your ground beef from, if any.

		Please select only one (1)
	Shopping	
Food safety issue last month?	No safety issue	
Store format:	Supermarket	○
Additional private testing?	No	
Price of ground beef ($/lb)	$3.00	
	Shopping	
Food safety issue last month?	Antibiotic residue	
Store format:	Club store	○
Additional private testing?	Yes	
Price of ground beef ($/lb)	$1.50	
I choose not to purchase my ground beef at any of these stores.		○

FIGURE 2 | Hypothetical consumer choice scenario example.

independent choice sets in which they selected between two shopping scenarios (Shopping A, Shopping B) and a "do not shop" option resulting in three different choice options per choice set (see **Figure 2** for an example of one of the choice sets used). Shopping scenario attributes were selected by consulting food safety scientists and a focus group session with U.S. shoppers. The final shopping scenario attributes and attribute levels used are provided in **Table 1**.

Five different prices were used in the choice design. A base ground beef price was established using prices provided by the U.S. Department of Labor's Bureau of Labor Statistics (BLS). The average price of ground beef was $2.25 per pound. Using this as a midpoint, we specified four additional hypothetical prices by adding and subtracting $0.15 and $0.75. Thus, there were five different prices with a spread of $1.50 per pound.

One Class I recall and one Class II recall were selected from a list of potential food safety recalls. *E. coli*, antibiotic residue, and "no food safety issue" were the three food safety issues (attribute levels) selected. *E. coli*, a Class I recall, was selected given the considerable amount of food safety research already conducted and the large investments made by the beef industry and government individuals to improve pre- and post-harvest *E. coli* food safety. Antibiotic residue, a Class II recall, was selected since antimicrobial residue and resistance is a rising concern among consumers. Current beef research is attempting to discover pre- and post-harvest ways to reduce potential antimicrobial residue in meat products. The "no food safety issue" was included to provide a control scenario.

Three store formats were used: supermarket, club, and convenience. About 81 percent of U.S. households purchase much of their food from these types of stores[8] (46). Among our respondents, ~95% indicated that they purchased food from these types of stores. In the event of a food safety recall, processors work with retail stores to secure the return of potentially harmful products from consumers. When a reasonable effort has been made to contact and retrieve potentially contaminated products, FSIS removes the food safety issue in question from current monitored recalls. No additional testing occurs to ensure that any remaining products are safe to consume. Since no further testing occurs, above the systematic and random sampling for new products shipped to stores, private stores could engage in additional testing to assure customers that food safety issues have been resolved. Thus, regardless of store format, we allow stores to engage in additional/on-site private testing as a measure of consumer quality assurance[9].

The length of time a food safety recall remains "current/active" varies. The objective of the study is to measure how much consumers discount ground beef after a food safety recall has

testing is conducted and the price for ground beef ($/lb). You will be shown two different stores and asked which one you would shop at, if any. Please answer as honestly as possible and in a manner that you think would reflect your true shopping attitude."

[8]We acknowledge that this potentially biases the results, as some consumers primarily purchase food at dollar, drug, organic/natural, convenience, ethnic, or online stores. However, ~95% of individuals who completed the survey indicated that supermarkets, club stores, and convenience stores were considered their primary source of grocery-type items. This is representative of the average U.S. consumer population.

[9]We recognize that not every store format may be able to conduct private testing. Reasons vary from logistic to cost-effectiveness. We do not attempt to answer if it is feasible for certain store formats to engage in testing and at what price premium this becomes cost-effective.

TABLE 1 | Contract attributes and levels for stated choice experiments given a hypothetical food safety recall.

Contract attribute	Description	Levels	
		Level names	Number of levels
Product	Meat product available for individuals to purchase	Ground beef (1 lb.)	1
Time since last food safety issue	Indicates the time since the initial notification from USDA-FSIS to the public about a food safety issue	4 weeks	1
Food safety issue	Indicates the type of food safety issue that has USDA-FSIS has notified the public about, if any	None, *E. coli*, antibiotic residue	3
Private testing	"Yes" indicates the store will provide additional testing to ensure the food safety recall is contained, and "No" otherwise	Yes, no	2
Store format	Indicates the store individuals can purchase their ground beef from	Supermarket, club, convenience	3
Price	Advertised price ($/lb.) for ground beef	$1.50, $2.10, $2.25, $2.40, $3.00	5

occurred, but *after* the initial potential threat to human health has decreased, preferably to zero. It is difficult to determine when the minimal potential threat to human health approximates to zero. A food safety recall may be "current/active" for several months or years, but it is unlikely that the threat to human health remains constant through time. One way to proxy whether the potential threat to human health approximates to zero is through an epidemiological outbreak curve which tracks reported health occurrences through time. Using epidemiological outbreak curves from the Centers for Disease Control and Prevention (CDC) for *E. coli*-O157, a time frame of 1 month was selected[10]. Thus, given that a food safety issue potentially happened in the prior month and no immediate health threat is likely present to consumers, the potential discount to ground beef can be viewed as an "intermediate-term" impact.

Given one meat product, one time period, three hypothetical food safety issues, two levels of private testing, three store formats, and five prices, there are 8,100 different possible choice sets $\left((1 \times 1 \times 3 \times 2 \times 3 \times 5)^2\right)$ that could be constructed. Thus, we opted to use an orthogonal balanced incomplete (fractional) block design to capture the main and first-order interaction effects. This design is superior to other commonly used designs since it tends to be more reliable, maintains adequate flexibility, accurately captures extreme options, and reduces the burden of excessive questions on respondents (47). PROC OPTEX in SAS was used to develop the incomplete block fractional factorial design, providing 120 random choice sets, which were then grouped into 20 blocks, with each block containing six choice sets that could be used to identify main and interaction effects. The D-efficiency criterion (89.72%) was used to assess the optimal block design efficiency. Each choice set represents a question that a respondent may face in the survey, with each question (choice scenario) asking respondent to choose between three shopping scenarios: "Shopping A," "Shopping B," and "Do Not Shop" (an "opt out" option). Each shopping scenario contained attribute information about shopping scenario prices, food safety issues, and level of private testing. Given the large number of choice scenarios, the choice scenarios were blocked into 20 sets of 6 scenarios (or questions). Blocking was done using PROC OPTEX in SAS. Individuals who agreed to participate in the survey were randomly assigned to one of the blocks of six questions (or choice scenarios) followed by questions concerning their consumption and cooking habits, as well as access and preference for food safety information. Prior to answering the set of choice questions, participants were presented with a cheap talk script. The six choice questions (sets) were randomly ordered to avoid any potential order bias. After completing the stated choice experiment and subsequent questions, participants were asked some follow-up demographic questions, after which they then exited the survey.

METHODS

Random Utility Maximization Model

The Random Utility Maximization framework (RUM) assumes individuals are utility maximizers, where utility is derived from the attributes of the product or good being consumed (48). Given that the researcher only observes the choice of the consumer, it is assumed that the individual's utility function is represented as $U_{nit} = \boldsymbol{\beta}'\mathbf{X}_{nit} + \varepsilon_{nit}$, where X is a vector of attributes observed for individual n $(1, \ldots, N)$ when choosing alternative i $(1, \ldots, I)$ in choice set t $(1, \ldots, T)$, β is a vector of parameters to be estimated, and ε is the unobserved part of utility. Given that ε is unobserved, we treat ε as a random variable. Following Train (49), we assume ε is distributed Extreme Value Type I. Train (49) explains that this distributional assumption does not differ substantially from the normal distribution, but does allow for more aberrant behavior given it has fatter tails. In addition, this distributional assumption allows for a closed-from solution for the choice probabilities of interest in this study. The probability of an individual choosing alternative i over alternative j in choice set t is given by the

[10]After initial confirmation of a food safety outbreak, the CDC continues to monitor situation for about one month. CDC stops monitoring most food safety issues after one month since most of the harmful product has either been recalled or diminishing safety incidences. This does not imply that there are no more food safety issues but rather that they are not actively monitoring the situation anymore. Thus, 1 month is a broad way of defining the length of time to resolve food safety issues.

Random Utility Multinomial Logit (RUM-MNL) function:

$$P_{nit} = \frac{exp(V_{nit})}{\sum_{j=1}^{J} \exp\left(V'_{njt}\right)} \tag{1}$$

where $V_{nit} = \boldsymbol{\beta}'\mathbf{X}_{nit}$.

The RUM-MNL assumes that all individuals have similar views on food safety recall attributes. It is likely that these views vary across individuals and that groups of individuals have similar tastes and preferences. We allow for this type of heterogeneity using a latent class model in which attribute estimates are assumed to be similar within groups/classes but different across groups/classes. The approach and number of classes to include was determined using a combination of the Akaike information criterion [AIC; (50)], adjusted Bayesian information criterion [BIC; (51)], and relevant class sizes consisting of at least 20% of the individuals (52, 53). Thus, we modify Equation 1 to allow estimation of classes, *C*, given as:

$$P_{nit} = \sum\nolimits_{c=1}^{C} P_{nc}\frac{exp(V_{nit})}{\sum_{j=1}^{J} \exp\left(V'_{njt}\right)} \tag{2}$$

where P_{nc} is the probability of individual n being in class c, V_{nit} is the same as described above expect now the parameters are class specific (i.e., β_c). P_{nc} is assumed to be a function of individual-specific characteristics that describe the characteristics of the group. That is: $P_{nc} = \frac{exp(\gamma_c'\mathbf{Z}_n)}{\sum_{r=1}^{R}\exp(\gamma_r'\mathbf{Z}_n)}$, where γ_c is a vector of class parameters to be estimated and $\mathbf{Z}_n$ is a vector of individual specific covariates. We assume class membership is determined by trust in informational sources, buying behavior, and cooking behavior (6–8).

Random Regret Minimization Model

Nearly all hypothetical choice experiments have been based on the behavioral assumption of utility maximization. Decision rules within this framework aim to model the marginal (dis)utility attached to alternative-specific attributes. Despite the popularity of the utility maximization framework, various attempts have been made to relax its underlying premises which at times lack behavioral realism. One alternative framework, the Random Regret Minimization (RRM), allows a chosen alternative to depend on the anticipated performance of non-chosen alternatives. This behavioral variation in the decision rule implies that the selection of a specific alternative is affected by the relative (non)performance of one or more non-chosen alternatives. If one or more of the alternatives perform better than the chosen alternative, then this choice would cause an individual "regret." Thus, the behavioral assumption assumes that an individual seeks to minimize anticipated regret rather than maximize utility from a given choice (54).

Empirical evidence supports this behavioral modification of regret compared to utility maximization. For example, microeconomics and psychology both find that regret is an important determinant in choice behavior (55–58). Regret is particularly present when making risky choices where individuals must absorb (potentially) short or long-term sub-optimal decisions. Likewise, there is evidence that modeling regret, compared to utility maximization, is more appropriate when there are significant potential losses or gains involved (20).

The forgoing discussion about model estimation in this context can now be modified to show how the Random Regret Minimization model differs from the commonly accepted assumption of Random Utility Maximization. The RUM aims to capture the marginal (dis)utility attached to alternative-specific attributes. The RRM assumes individuals minimize the sum of binary regrets between alternatives. Thus, for a given alternative i, regret occurs when it is outperformed by alternative j on attribute m. Letting there be m $(1, \ldots, M)$ attributes, regret can be modeled as:

$$\begin{aligned} RR_i &= R_i + \epsilon_i \\ &= \sum\nolimits_{j \neq i} \sum\nolimits_{m=1}^{M} \ln\left(1 + \exp\left(\left[\delta_m \times \left(x_{jm} - x_{im}\right)\right]\right)\right) + \epsilon_i \end{aligned} \tag{3}$$

where RR_i is the total regret associated with alternative i, R_i is the observed regret associated with alternative i, ϵ_i is the unobserved regret associated with alternative i, δ_m is an estimated parameter associated with attribute x_m, and x_{im} and x_{jm} are values associated with x_m for considered alternative i and alternative j. Regret for alternative i approaches zero with respect to attribute m when the difference between x_{jm} and x_{im} is at least <0. The Logsum formulation of attribute-level regret in Equation 3 acts to smooth the regret-function and allows for an approximation that is differentiable and globally concave (59).

Similar to the RUM framework, different models arise given different distributional assumptions for ϵ_i. If the negative of the errors (ϵ_i) is distributed as Extreme Value Type I, the choice probabilities gives rise to the Random Regret Minimization Multinomial Logit (RRM-MNL) model, where the choice probability can be written as:

$$P_{nit} = \frac{exp(-R_{nit})}{\sum_{j=1}^{J} \exp\left(R'_{njt}\right)} \tag{4}$$

where R_{nit} is the random regret for individual n choosing alternative i in choice set t. It is important to note that Equation 4 is maximizing the negative of random regret, which is mathematically equivalent to the minimization of random regret (20).

We believe that the behavioral assumption of the model should not alter the presence of individual preference heterogeneity. Likewise, we believe that these taste preferences are still different across but similar within groups of consumers. The decision rule to identify classes/groups of individuals is the same as the rule used under the RUM-MNL framework. The latent class model is derived by modifying Equation 4 as follows:

$$P_{nit} = \sum_{c=1}^{C} PR_{nc} \frac{exp(-R_{nit})}{\sum_{j=1}^{J} \exp\left(R'_{njt}\right)} \quad (5)$$

where PR_{nc} is the probability of individual n being in class c, R_{nit} is the same as described above expect now with class-specific parameters. The specification of PR_{nc} follows that of the RUM-MNL model presented in the previous subsection.

Hybrid Model: Random Utility Plus Random Regret

It is unlikely that every individual or group of individuals views choice decisions under a regret minimizing or utility maximizing framework. Some individuals may aim to maximize utility while others may minimize regret. In our context of making decisions about potential ground beef decisions after a potential food safety issue some combination of utility maximization and regret minimization seems particularly important. Previous research suggests that there is significant variation in how individuals view the cost or likelihood of a food risk occurring (60). Proper categorization of individuals is important since managerial and policy decisions are likely to differ substantially between these groups. Whether groups of individuals exist, the relative size of said groups, and the differences in managerial and policy implications arising from these two groups can be empirically tested.

We test this hypothesis by using a latent class model where some classes/groups are constrained to be utility maximizing and others regret minimizing. This hybrid model specifies that some choice probabilities follow Equation 2 under the random utility framework while other choice probabilities follow Equation 5 under the random regret minimization framework. Hess and Stathopoulos (61) describe in detail how this type of model is specified and estimated using the framework provided for the random utility and random regret models. The optimal number of classes under each behavioral framework is determined using the latent class decision rule described for the other models previously discussed. We more deeply explore which socioeconomic covariates characterizing individual n are likely to be related to risk-minimizing or utility-maximizing behavior for food safety recalls using this hybrid framework.

Data Quality Checks and Methods of Comparison

Survey length and monetary compensation for survey completion were a potential concern for response quality, and thereby estimation (62, 63). Researchers traditionally overcome these issues by asking engagement or inattention questions randomly throughout the survey. Individuals who fail inattention questions are generally removed prior to estimation since they pose a significant threat to data quality and can lead to significant violations to axioms of revealed preferences (63, 64). Recent research suggests that inattentive individuals can be captured through a latent class model where one class is restricted to zero known as the "random response share" [RRS; (65)].

We determined where there are inattentive respondents in our survey by estimating Equations 1 and 4 and then statistically testing model fit against Equations 2 and 5 with two classes where one class is restricted to zero (65). All models were estimated in NLOGIT6. Latent class models under both behavioral frameworks identified 31% of respondents as producing random responses highlighting the importance of accounting for this class of individuals. A log likelihood test determined that by accounting for identified non-attentive individuals, model fit significantly improved. Thus, all models reported in subsequent tables were estimated using a latent class model where one class was restricted to zero to capture RRS.

RESULTS

Multinomial Logit Estimation Under Both Behavioral Frameworks

Table 2 presents estimates under two different behavioral assumptions: random utility maximization (RUM) and random regret minimization (RRM)[11]. The McFadden Pseudo R^2 values indicates a relatively decent fit to the data. Although the AIC and log likelihood values appear similar, suggesting statistically similarity between models, the traditional log likelihood tests can only be used to compare statistical differences between nested models. Since the RUM and RRM models are non-nested, traditional log-likelihood tests are inappropriate. The Vuong test (66) is one non-nested testing procedure that is applicable when there are two or more choice alternatives and the models may be observationally equivalent. The null hypothesis for the Vuong test is that the two behavioral frameworks are equally "close" or are representative of the true data generating process. The alternative hypothesis is that only one of the behavioral frameworks is closer or more representative of the true data generating process. However, the test cannot determine if the "closer" framework *is* the true data generating process. A Vuong statistic $<$-2 favors the alternative hypothesis, a value $> +2$ favors the null hypothesis, and a value between -2 and $+2$ is inconclusive. Using model information from **Table 2**, we calculate the Vuong test statistic. The test statistic is -4.12 implying that that the RRM (alternative model) is closer to the true data generating process than the RUM. Thus, the RRM is preferred in comparison to the RUM.

All parameters in **Table 2** have the expected sign and are statistically significant at the 0.01 level. While the models are statistically similar to each other and coefficient signs are all the same, the direct comparison of magnitudes of the coefficients across behavioral frameworks is not meaningful (67). Where RUM parameters signify the contribution of an attribute to an alternative's utility, RRM parameters signify the potential

[11]Model estimations converged with set convergence criteria (1e-6) based on the gradient using starting values from the corresponding standard multinomial model in NLOGIT. We ran several robustness checks changing tolerance criteria algorithmic parameters, and found that both coefficient estimates and class size were robust to these changes.

TABLE 2 | Latent class model estimation with random response share under alternative behavioral assumptions.

	Random utility maximization (RUM)			Random regret minimization (RRM)		
	Mean	**SE**	**WTP ($/lb.)**	**Mean**	**SE**	**WTP ($/lb.)**
Constant	0.587**	0.069		0.933**	0.137	
Price	−0.354**	0.032		−0.521**	0.053	
E. coli	−2.939**	0.101	−8.30	−4.393**	0.123	−6.31
Residue	−1.736**	0.045	−4.90	−2.816**	0.072	−3.77
Club store	0.732**	0.049	2.07	1.213**	0.073	2.60
Supermarket	1.069**	0.049	3.02	1.706**	0.072	3.87
Private testing	0.506**	0.036	1.43	0.801**	0.054	1.66
RRS	0.307**			0.309**		
McFadden R^2	0.235			0.233		
LL	−10,045			−10,072		
AIC	20,106			20,161		
N	11,9641			11,964		

***indicates significance at the 0.01 level.*

contribution of an attribute to the regret associated with an alternative conditional on non-chosen alternatives (20). Even though the magnitude of coefficients between the RUM and RRM frameworks cannot be directly compared, the relative odd ratios between parameters within the same framework is meaningful. Thus, we calculate the odd ratios between parameter estimates.

Under both frameworks, the likelihood of purchasing ground beef given an *E. coli* (Class I) recall is greater (i.e., more negative) than a food recall due to antibiotic residue (Class II). Both food recall estimates are negative indicating the odds of purchasing ground beef given either food safety recall decreases when either food safety issue is present. Respondents have lower odds to purchase ground beef given an *E. coli* recall relative to antibiotic residue in the past month. The odds of purchasing ground beef after an antibiotic residue recall compared to *E. coli* is 0.21–0.30, suggesting that respondents viewed *E. coli* as a greater threat to their health and therefore avoided purchases with greater frequency. We observe larger odds ratios under the RRM framework, suggesting that under risky food decisions, regret may be a statistically more important behavioral component than marginal utility. This supports the idea from Ajewole et al. (60) that individuals view food safety risks having an immediate impact on human health as more problematic than those with delayed impacts. Likewise, these results support our previous hypothesis that consumer valuations for food safety recalls are an increasing function of the relative probability of human illness and death. Thus, consumer reactions/valuations to Class I recalls (i.e., *E. coli*) should be larger in magnitude than Class II recalls (i.e., antibiotic residue).

The odds of purchasing ground beef at a supermarket is ∼40–63% greater than purchasing it at a club store ($e^{1.069}/e^{0.732} = 1.40$). Under the RRM framework, individuals have greater odds of purchasing ground beef at supermarkets. This result confirms the findings from Stern et al. (46), that in 2012, individuals purchased more food from supermarkets than from club stores. *Club Store* and *Supermarket* estimates are positive, indicating that individuals viewed both store formats as more viable locations to purchase ground beef when compared to convenience stores. If stores were to adopt private food safety testing, the odds of purchasing ground beef would increase by ∼65–120% depending on the behavioral framework.

The differences in odd ratios between behavioral frameworks has potential important managerial and policy implications targeted at reducing food safety issues across different health classifications. Compared to the RUM framework, the RRM estimates suggest that individuals view *E. coli* as being more harmful than antibiotic residue. In addition, individuals have greater odds of purchasing ground beef if there were private store testing. Policies based on estimates from RRM would imply conducting less research and development for pre- and post-harvest practices to reduce antibiotic residue in meat products and a greater need for private store testing.

Elasticities and Willingness-To-Pay Estimates

Direct interpretation of estimated coefficients from the behavioral frameworks in **Table 2** is not straightforward. One alternative is to calculate and compare direct choice elasticities. Elasticities allow comparison across attributes within a behavioral framework, but interpretations of elasticities within a given framework may differ. Under the RUM framework, elasticities depend only on the performance or choice probability of the specific alternative. However, given the behavioral premise of the RRM framework that regret for a given alternative is based on the relative performance of non-chosen alternatives, interpretation of elasticities is slightly different. Namely, changes in the alternative attribute depend on the relative performance of all the alternatives in the choice task being assessed.

Our experimental design was an unlabeled choice in which individuals selected between shopping experiences. Calculating an elasticity for each store would not yield additional information since there is no intrinsic value in the elasticity differences

TABLE 3 | Direct elasticities and relative differences for latent class model with random response share.

Attribute	Random utility maximization (RUM)			Random regret minimization (RRM)			Elasticity ratio abs(RUM)/abs(RRM)
	St1	St2	St1-St2	St1	St2	St1-St2	St1-St2
Price	−0.340**	−0.340**	0.000	−2.140**	−2.017**	−0.123	0.001
E. coli	−0.305**	−0.303**	−0.002	−4.320**	−4.381**	0.061	0.026
Residue	−0.349**	−0.355**	0.006	−1.516**	−1.260**	−0.256	0.025
Club store	0.118**	0.133**	−0.015	0.584**	0.573**	0.011	1.343
Supermarket	0.172**	0.173**	−0.001	0.766**	0.723**	0.043	0.021
Private testing	0.111**	0.120**	−0.009	0.554**	0.568**	−0.014	0.615

***indicates significance at the 0.01 level.*

between "Shopping A" and "Shopping B" for a given attribute. Thus, following Thiene et al. (15), we calculate and report the mean difference between "Shopping A" and "Shopping B." Due to these differences in the interpretation of elasticities between frameworks, it is more appropriate to calculate an elasticity ratio. We calculate this as the ratio between the absolute value of the mean difference of the RUM framework divided by the absolute value of the mean difference of the RRM framework. A ratio >1 indicates an attribute is more elastic under the RUM framework. As the ratio approaches zero, it implies that the RRM elasticity is more elastic.

Table 3 reports the direct elasticities for shopping scenarios A and B, the difference between these scenarios, and the elasticity ratio. All elasticities in both frameworks are significant at the 0.05 level, all attributes have the expected signs, and attributes are relatively small. Five of the six attributes become more elastic under the RRM framework than in the RUM framework. Most attributes were significantly more elastic under the RRM framework compared to the RUM framework. The only noticeable difference is that of *Private Testing* which tended to be more elastic under the RUM framework.

Under both frameworks, choices made in *Supermarkets* are more elastic than those made in *Club Stores*. This result may arise from consumers who shop at supermarkets, buy small amounts of select items. Thus, these consumers are likely to be more price sensitive, whereas club store consumers generally buy bulk amounts of products. Under the RUM framework, Residue (Class II) is more elastic than *E. coli* (Class I), but the opposite is true under the RRM framework. This shows that using an appropriate behavioral framework is important in determining consumer attitudes toward food safety.

Willingness-to-pay (WTP) is another method to examine and compare alternatives. WTP calculations are conditional on the behavioral framework used and have been frequently used to determine valuation of environmental amenities [e.g., (68)], food attributes [e.g., (69)], and reductions in risk [e.g., (70)]. Under the RUM framework in Equation 1 where all the non-cost and cost attributes enter the utility function, WTP estimates can be estimated as:

$$WTP_{RUM} = -\frac{\beta_t}{\beta_c} \qquad (6)$$

where t represents any non-cost attribute and c is the cost attribute. Thus, the WTP is the ratio of attribute coefficients. The behavioral assumptions under the RRM framework imply a different WTP formulation. Using Equation 3, where all the non-cost and cost alternatives enter the regret function, Chorus (67) shows that the WTP can be estimated as:

$$WTP_{RRM} = -\frac{\beta_t}{\beta_c}\frac{\sum_{j\neq i}\left\{\frac{1}{1+\frac{1}{\exp[\beta_t(x_{ji}-x_{it})]}}\right\}}{\sum_{j\neq i}\left\{\frac{1}{1+\frac{1}{\exp[\beta_c(x_{jc}-x_{ic})]}}\right\}} \qquad (7)$$

where j, i are attributes, t is the non-cost alternative, and c is the cost attribute. Here, it is relatively straightforward to see how the WTP_{RRM} is a weighted version of the WTP_{RUM}, where weights are determined by the relative performance of non-chosen alternatives.

WTP estimates ($/lb.) are reported in **Table 2** for the RUM and RRM frameworks. Under the RUM framework, individuals were willing to pay an additional $1.43 per lb. of ground beef if a store engaged in additional food safety testing. Consumers were willing to pay approximately a dollar more to purchase ground beef in Supermarkets compared to club stores. Consumers discounted ground beef by ∼$8 ($5) per pound if an *E. coli* (antibiotic residue) recall occurred in the prior month. Given that the discount was larger than the average price of ground beef, this result implies that even though consumers may be willing to shop they would not likely purchase ground beef after these types of events.

The RRM estimates of WTP are much different from RUM estimates. The discount from an *E. coli* recall on ground beef was ∼$6 per pound, compared with $4 per pound for an antibiotic residue recall. These estimates are approximately $2 and $1 lower than corresponding estimates under the RUM framework, respectively. Differing WTP estimates were found for other attributes as well. The lower WTP estimates using the RRM framework may indicate a "regret adjusted" WTP, whereas WTP under RUM encompass a "risk/regret" premium. That is, risk-averse consumers may prefer to minimize risk (regret) rather than maximize utility *in situations* dealing with potentially hazardous food risks. The differences found between the behavioral frameworks emphasizes the need to identify correctly individuals purchasing behavior intentions in order to make viable managerial and policy decisions.

Comparison of Latent Class Models and a Combined Framework

Table 4 displays the results for the latent class models estimated under the RUM, RRM, and RUM+RRM frameworks. Three optimal groups of individuals were identified under each framework using the decision rule to identify major classes based on AIC and BIC: two RUM groups under RUM framework, two RRM groups under RRM framework, and one RUM + one RRM group under the hybrid framework. Our previous results suggest that correctly identifying and categorizing individuals as either RUM or RRM. We now attempt to differentiate between consumer behavior related to risky choice-making based on respondent personal characteristics. As such, a combination of organizational trust, shopping habits, and cooking arrangements were used to attempt to understand the sociodemographic makeup of each class. These factors were selected based on strong predictors of food purchase decisions identified by prior studies of food safety and marketing [e.g., (71–74)].

Approximately 8% of individuals were identified as producing random responses across all models. This suggests regardless of the underlying behavioral framework, the random response method (65) was able to identify a similar magnitude of individuals who were inattentive. The McFadden Pseudo R^2 indicates a relatively good fit to the data for each of the models. We compared model fit across frameworks using the Vuong test. We calculated the Vuong test statistic for each binary comparison. In total, we have three test statistics, RUM vs. RRM, RUM vs. RUM+RRM, and RRM vs. RUM+RRM. We find RUM was inferior to either RRM or RUM + RRM but both RRM and RUM+RRM models have similar statistical fit (−4.12, −3.22, and 1.70, respectively). This suggests that the behavioral assumptions have an impact upon model performance.

Estimated coefficients from choice attributes across all the frameworks are significant at the 0.05 level and have the expected signs. A negative price sign indicates that as price goes up the odds of purchasing ground beef decreases consistent with economic theory. Negative coefficients on *E. coli* and Residue are likewise consistent with economic and food safety theory, indicating that when a food safety recall occurs, the odds that a consumer purchased ground beef decreased. One question specific to this paper is the relative magnitude of an *E. coli* (Class I) recall compared to an antibiotic residue (Class II) recall. **Table 4** suggests that the odds of purchasing ground beef after an *E. coli* recall were lower than after an antibiotic residue recall across all frameworks and groups of individuals.

As previously mentioned, the relative magnitude of coefficients across behavioral frameworks cannot be compared, but the relative magnitude of coefficients across models can (75). Under each behavioral framework, there is one class/group of consumers which is relatively less likely to purchase ground beef in the event of an *E. coli* recall. For example, under the RUM framework, the coefficient ratio of *E. coli* to Residue is 1.87 and 1.37 for individuals identified in class two and class one respectively—or about 36% smaller. Similar comparisons can be made for the RRM and RUM+RRM frameworks.

Club Store and *Supermarket* both have positive coefficients, indicating that consumers view these store formats as viable locations to purchase ground beef. However, the larger coefficient on *Supermarket* compared to *Club Store* across all behavioral frameworks and classes of individuals suggests that the odds of purchasing ground beef are greater at a supermarket than at a club store. The coefficient for P*rivate Testing* is likewise positive, indicating that if stores were to engage in private testing of meat products, the odds of consumers purchasing ground beef from any store format would increase.

Class Specific Sociodemographic Attributes

The individual characteristics making up each consumer class (or segment) indicate that across behavioral frameworks, specific types of trust play an important role in ground beef purchases. Trust in each class is measured as the difference between the number of sources consumers found to be very helpful vs. not helpful. Our hypothesis is that as trust increases, so, too, will some individuals' odds to purchase ground beef. Across all classes of individuals and behavioral frameworks, as governmental trust increased, so, too, did the odds of buying ground beef. These results support the conjecture that if consumers trust the government, or specifically in the case of recall information from FSIS, then the odds of purchasing ground beef after a food recall in the previous month would increase. This likely indicates that trust from other non-USDA governmental branches can have trust "spillover" effects on ground beef purchasing.

Trust in advocacy groups never increased ground beef consumption, but for select groups of consumers, the odds of purchasing ground beef decreased. This decrease in odds of purchasing ground beef is likely due to advocacy groups being generally oriented toward exposing or promoting negative information about ground beef consumption. Surprisingly, as trust increased in stores, the odds of purchasing ground beef decreased. There appears to be two conflicting results. First, **Table A4** suggests that a large majority of individuals do not view stores as a helpful source of food safety information. Second, **Table 2** suggests that consumers are willing to pay a premium for ground beef if stores engaged in private testing. We are unsure of why store trust would decrease ground beef purchasing, but we do note that the relative magnitude of *Private Testing* is larger for classes of individuals where store trust is low. Trust in Producers, Media, and *Family* all have no statistical impact on identifying class membership based on ground beef purchasing behavior. Thus, the increasing presence of producer promotion programs may do little to increase the odds of purchasing ground beef given a food safety recall.

Food purchasing and cooking behavior were also examined as potential individual attributes which could explain class identification. These two groups of characteristics have been used in studies to help explain food purchase decisions (76). We find that the self-identified proportion of groceries purchased by

TABLE 4 | Latent class estimation with random response share under alternative specifications.

	Random utility maximization (RUM)				Random regret minimization (RRM)				Hybrid model (RUM + RRM)			
	Class 1		Class 2		Class 1		Class 2		Class 1—RUM		Class 2—RRM	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Choice Attributes												
Constant	0.601*	0.149	2.465*	0.191	0.413*	0.079	1.315*	0.097	2.250*	0.187	0.423*	0.081
Price	−0.498*	0.060	−0.311*	0.064	−0.349*	0.037	−0.198*	0.038	−0.324*	0.064	−0.360*	0.038
E. coli	−4.281*	0.130	−1.650**	0.135	−2.886*	0.116	−1.024*	0.080	−1.833*	0.140	−2.947*	0.125
Residue	−3.117*	0.092	−0.882*	0.102	−1.970*	0.064	−0.567*	0.063	−1.011*	0.107	−2.032*	0.067
Club store	1.079*	0.079	0.720*	0.087	0.636*	0.053	0.530*	0.065	0.835*	0.090	0.628*	0.055
Supermarket	1.675*	0.076	0.836*	0.085	1.049*	0.053	0.628*	0.064	0.962*	0.089	1.059*	0.054
Private testing	0.708*	0.059	0.619*	0.066	0.447*	0.039	0.440*	0.048	0.676*	0.068	0.447*	0.040
Class Attributes												
Constant	1.825*	0.656	0.835	0.733	1.694*	0.587	0.711	0.675	0.607	0.657	1.591*	0.568
Trust—government	0.257*	0.064	0.199*	0.071	0.257*	0.064	0.204*	0.071	0.212*	0.067	0.257*	0.060
Trust—advocacy	−0.488	0.256	−0.625**	0.280	−0.435	0.243	−0.584**	0.268	−0.526**	0.253	−0.381	0.228
Trust—producer	−0.047	0.118	0.075	0.128	−0.075	0.112	0.043	0.124	0.028	0.118	−0.088	0.106
Trust—store	−0.230**	0.096	−0.151	0.105	−0.244*	0.093	−0.165	0.103	−0.194**	0.096	−0.258*	0.087
Trust—media	−0.003	0.045	0.050	0.049	−0.013	0.043	0.039	0.047	0.031	0.044	−0.0186	0.040
Trust—family	0.123	0.090	0.108	0.100	0.114	0.088	0.104	0.099	0.118	0.094	0.119	0.082
Buy—all	−0.368	0.624	−0.259	0.680	−0.284	0.556	−0.210	0.616	−0.282	0.601	−0.333	0.541
Buy—majority	−0.528	0.636	−0.434	0.696	−0.440	0.566	−0.334	0.632	−0.342	0.613	−0.462	0.548
Buy—equal	−0.696	0.719	−0.532	0.796	−0.718	0.642	−0.534	0.730	−0.505	0.711	−0.729	0.624
Cook—I	0.269	0.431	0.771	0.498	0.226	0.424	0.788	0.496	0.838	0.470	0.230	0.399
Cook—we	0.776	0.453	1.029**	0.517	0.683	0.427	0.968	0.498	1.034**	0.476	0.697	0.406
Class Probability	0.627*	0.015	0.296*	0.015	0.617*	0.016	0.302*	0.015	0.310*	0.015	0.603*	0.016
Model Performance												
RRS	0.076*				0.080*				0.085*			
McFadden R^2	0.285				0.282				0.282			
LL	−9,391				−9,436				−9,429			
AIC	18,859				18,949				18,935			
N	11,964				11,964				11,964			

*, **indicates significance at 0.05 and 0.01 level respective.

consumers has little impact on the odds of purchasing ground beef. One plausible explanation for this is that home meal menus are jointly created and thus ground beef is on the shopping list regardless of who purchases the food. Evidence for this hypothesis should appear in the household cooking arrangement. If menus are jointly created, then cooking jointly should be significant. We find that only the *Cook-We* arrangement significantly increased the odds of ground beef purchases, but only for a select subset of individuals—generally, the class with a smaller class probability. Thus, this hypothesis holds but is not true across all consumers. Other cooking did not significantly explain class/group membership.

Classes Across Behavioral Frameworks

Comparing the attributes that make up each class within and across behavioral frameworks reveals persistent consumer behavior. Generally, there are two broad groups of consumers across all frameworks. The first group is identified as viewing an *E. coli* (Class I) or antibiotic residue (Class II) as similar, preferring to purchase ground beef at supermarkets and trusting government sources, while distrusting stores. This group consists of 63% of respondents. This group is seen in the RUM-class1, RRM-class2, and RUM+RRM-class2 classes. The second group consisted of consumers who view *E. coli* as a more problematic food safety issue than antibiotic residue, trusted government, distrusted advocacy groups, and where cooking was shared among household adults. This group consists of 30% of respondents. This group is seen in the classes RUM-class2, RRM-class2, and RUM+RRM-class1.

Results up to this point show overwhelming support for the need to correctly identify individuals who are either utility-maximizing or regret-minimizing. Columns 10–13 of **Table 4** display the estimates for the RUM+RRM model, where one class is restricted to RUM and the other is RRM [e.g., (61)]. The first class, categorized as RUM, consisted of 31% of the population. The second class, categorized as RRM, consisted of 60% of the population. These individuals trust government sources and distrust stores as a source for food safety information.

These consumers account for the performance of non-chosen alternatives in making choices and attempt to minimize regret in purchasing potentially risky foods. This appears to align well with intuition in the context of food safety recalls. For example, consumers view all food as inherently "safe" when going to the store to purchase food. Under a situation where a food safety recall has occurred in the previous month, consumers may perceive that the likelihood of purchasing "safe" or "healthy" food is <1. This could cause them to become risk averse and thus avoid making a food purchasing decision in the event the food safety issue has not been sufficiently resolved. The consumer may wish to minimize the regret of making an incorrect food purchase decision and avoid any potential immediate or long-term effects due to, for example, "food poisoning" [12]. The fact that the two subgroups appear across different behavioral frameworks emphasizes the point that correctly modeling consumer decision making is important to the analysis and evaluation of policy options. Under stricter assumptions, one could say that 60% of the individuals in the RUM model were "misclassified," as they do not aim to maximize utility when purchasing ground beef but rather minimize potential regret when making their decision. A corollary argument could be made for 30% of individuals in the RRM framework. However, a combination of the two classes appears to allow for better identification. This is particularly important given that both models are statistically similar and, as we will see in the next section, different conclusions for industry and governmental policy could be drawn.

Price as a Policy Mechanism

We now explore how differences across behavioral frameworks give rise to different implications for government policy and industry responses to a given food safety recall. Price is the primary mechanism that stores can use to incentivize ground beef purchases. One reason stores discount price after a food safety recall is to encourage ground beef purchases to offset an individual's "food safety risk premium."

We explore how different price discounts affect the probabilities of various ground beef purchasing choices. We do so by using the estimates from **Table 4** to calculate shifts in consumer choice probabilities and total changes given either a 10 or 50% price discount. Since we have an unlabeled hypothetical choice experiment, we allow the discount to occur separately in either "Shopping A" or "Shopping B" and then average the change in choice probabilities. We call the shopping experience where the discount occurred as *Discounted*, the shopping experience where the discount was absent *Non-discounted*, and the choose-not-to-shop option *No purchase*.

Table 5, panel (a), reports these findings across the three different behavioral models estimated in the paper (RUM, RRM and RUM+RRM). Column one is the different price discounts and discount scenarios. Columns two, four, and six [labeled "Change in choice probability (%)"] are the average changes in choice probabilities for the three behavioral models for each respective shopping scenario. Columns three, five, and seven [labeled "Total change (%)] report the percentage share of the increase/decrease in choice probabilities; in other words, how much of the change in choice probabilities is attributed to either *Non-discounted* or *No purchase* individuals changing purchase behavior?

Comparing changes in choice probabilities across behavioral models reveals several insights. First, all the signs on the coefficients are as hypothesized—a decrease in the price increases the choice probability in the *Discounted* store. Second, the changes in choice probabilities under the RRM framework are greater than RUM+RRM, which are greater than the RUM framework (e.g., 1.06 > 1.05 > 0.98 for a 10% decrease in price). As the price discount increases, this effect becomes more pronounced. Given either a 10 or 50% reduction in price, more individuals are predicted to purchase ground beef under the RRM framework than under the RUM framework. This aligns with our previous findings that choice attribute elasticities were more elastic under RRM compared to RUM (see **Table 3**). It also implies that understanding which behavioral framework applies to ground beef purchases could affect policy decision making and industry response. For example, knowing that choices are more sensitive to price changes under RRM than RUM, price would not need to be discounted as much to ensure the same market share. Thus, a 10% price discount under RUM would achieve the same change in choice probability as a 9.24% price discount under an RRM framework.

Third, a decrease in the price of the affected alternative incentivizes some individuals who were not purchasing ground beef to purchase ground beef. This is seen by a non-zero value for *No Purchase*: −0.43, −0.43, −0.44 under RRM, RUM+RRM, and RUM, respectively. For a 10% price discount 0.43, 0.43, and 0.44% of respondents would now purchase ground beef under the different respective frameworks. While the shift is slightly larger under an RUM framework, the share of the *No Purchase* change relative to the total change is ∼45% (40%) of the increase in choice probability under the RUM (RRM) framework. This implies that under an RUM framework, more of the change in choice probability comes from people willing to switch from not purchasing ground beef to purchasing ground beef rather than shifting consumption between stores. Given that price is one product attribute in which stores compete, the results indicate that one store's prices have a larger negative/competing effect on another store under an RRM framework than under an RUM framework.

We now explore how stores engaging in testing after a food safety issue would affect consumer choice probabilities. **Table 2** reported WTP estimates for *Private Testing* under both RUM and RRM frameworks. We take the average private testing premium between these frameworks, $1.50 per lb., and then add it to the average price of ground beef in our study and assume that price

[12]It could be possible that a specific consumer could be regret minimizing in some circumstances but maximize utility in others. Thus, our premise is not that consumers are either one or other but rather circumstances could arise, in our case a food recall in the previous month, where consumers wish to minimize regret for making choices that could lead to potentially negative consequences. This conclusion appears to align well with the increased sensitivity of U.S. population toward health and healthy foods in recent years.

TABLE 5 | Predicted change in choice probabilities given various price discounts.

	Random utility maximization (RUM)		Random regret minimization (RRM)		Hybrid model (RUM + RRM)	
	Change in choice probability (%)	**Total change (%)**	**Change in choice probability (%)**	**Total change (%)**	**Change in choice probability (%)**	**Total change (%)**
Panel (a)						
10% price discount						
Discounted[a]	0.98	100.00	1.06	100.00	1.05	100.00
Non-discounted[a]	−0.55	−55.47	−0.63	−59.74	−0.62	−58.75
No purchase[a]	−0.44	−45.53	−0.43	−40.26	−0.43	−41.25
50% price discount						
Discounted[a]	5.01	100.00	5.31	100.00	5.28	100.00
Non-discounted[a]	−2.73	−54.39	−3.11	−58.53	−3.06	−57.89
No purchase[a]	−2.29	−45.61	−2.20	−41.47	−2.23	−42.11
Panel (b)						
$3.75 price level						
Price increase[a]	−6.24	−100.00	−6.79	−100.00	−6.67	−100.00
No–price increase[a]	3.55	56.82	4.20	61.87	4.04	60.51
No purchase[a]	2.69	43.18	2.59	38.13	2.64	39.49

[a]*Average effects, author calculations.*

is fixed across shopping venues. We then set this as the price level and observe changes in choice probabilities. We interpret these changes in choice probabilities as measures of market share that a store could capture by engaging in additional store food safety testing. **Table 5**, panel (b), reports the changes in choice probabilities. At $3.75 per lb. ($2.25 + $1.50 testing premium), the choice probability would increase on average by 6%. Note that the sign is negative for the *Discounted store* since the price was raised.

DISCUSSION AND CONCLUSIONS

This paper empirically examined how consumers perceive and value different classes of food safety recalls. Specifically, we compared *E. coli* (Class I) and antibiotic residue (Class II) ground beef recalls in the prior month. A hypothetical choice experiment was used where consumers selected among different shopping experiences and choice attributes that included type of recall, store format, and private testing. Data were modeled using two competing behavioral frameworks: the commonly assumed random utility maximization (RUM) framework and the newer random regret minimizing (RRM) framework.

Consumers were less likely to purchase ground beef given an *E. coli* recall in the prior month compared to an antibiotic residue recall. This was consistent with our hypothesis that consumer valuations for food safety recalls are a function of the relative probability of illness and death. The odds of purchasing ground beef were higher in supermarkets compared to club and convenience stores and if the store engages in private food safety product testing. Results were consistent across behavioral frameworks and model specifications.

We found that the RRM or the hybrid model (RUM + RRM) was the preferred model specification. The hybrid specification shows that about 60% of individuals are regret minimizer while only 30% maximize utility. If a RUM framework were used, this would imply 60% of individuals would be "misclassified." The model significantly affected direct elasticity estimates, classification of consumers, and policy/industry price mechanisms. Results were consistent with previous studies that the behavioral assumption of random regret appears better suited to model risky choices having potential losses (for example, food poisoning). Likewise, results predicted behavioral responses may differ substantially conditional on behavioral framework.

While the magnitude of difference between behavioral frameworks is modest, the implied aggregate impact on ground beef consumption is economically significant. By comparing the relative discount of *E. coli* to antibiotic residue, an estimate of the necessary investment by the industry can be obtained. More importantly, this study speaks to policy and industry debates regarding the need to reduce antimicrobial use in livestock production, which could lead to reduced antibiotic residue in meat products and ultimately lower antimicrobial resistance in human health. Since consumers value antibiotic residues <*E. coli* contamination, any investment in research and development to reduce antibiotic residue in beef supply chain should be no more than 60% of the total research and expenditure of *E. coli*. However, given that antibiotic residue is generally known to not cause immediate health concerns, this estimate is likely an extreme upper bound. By how much likely depends on the relative weighting policy makers place on mitigating Class II recalls relative to Class I recalls given finite food safety funding. These results provide new, systematic evidence that both the class of food safety recall and the behavioral framework have substantial impacts on policy decisions and suggest that strengthening organizational trust has the potential to increase meaningfully the efficiency of research and development on antibiotic residue.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

This study involved human participants without deception and minimal risks. The study was approved by the IRB at Kansas State University. All participants were provided a written informed consent to prior to study participation.

AUTHOR CONTRIBUTIONS

ED generated the research question, designed the experiment, conducted the experiment, conducted the analysis, wrote, and edited the paper. KA designed the experiment, conducted the experiment, conducted the analysis, and edited the paper. JB designed the experiment, conducted the analysis, and edited the paper. TS designed the experiment, wrote and edited the paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2020.00611/full#supplementary-material

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Impacts of African Swine Fever on Pigmeat Markets in Europe

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African Swine Fever (ASF) is a highly contagious animal disease which can cause disruptions in the international trade of pigs and products derived from pigs. During 2014–2019 ASF was introduced into several member states in the European Union (EU), including the Baltic states and Poland (2014), Czech Republic and Romania (2017), Belgium, Bulgaria and Hungary (2018), and Slovakia (2019). The objective of this study was to analyze how the ASF epidemic has contributed to the production, export, and prices of pigmeat and to the national pig inventory (number of pigs) in 11 EU member states. The data included country-level statistics on the pig markets and ASF outbreaks observed during 2010–2019. The data were first analyzed descriptively. Following this, a system of four equations was specified and estimated by using seemingly unrelated regression method. The results indicated that the consequences of ASF to the pigmeat markets are complex and may differ by country. They suggest that an ASF outbreak can reduce the production of pigmeat, export quantities and the national pig inventory in the short and medium term. On average, those new cases of ASF reduced the exports of pigmeat by close to 15% and the production quantity by more than 4% in the year after the cases had occurred, and the national pig inventory by 3–4% both in the current and the next year. However, only indirect effects on pigmeat prices were observed.

Keywords: African swine fever, trade, pigmeat, supply, markets, producer price, export

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INTRODUCTION

African swine fever (ASF) is a notifiable contagious animal disease, the control of which is governed by national and international regulations and agreements. Apart from the island of Sardinia in Italy, the European Union (EU) was free from ASF for many years until the disease was introduced into Lithuania in 2014. However, the disease was introduced into non-EU countries in Eastern Europe already a few years earlier, namely into Georgia (in April 2007), the Russian Federation (2007), Ukraine (2012), and Belarus (2013). Since 2014, the disease has spread to nine Eastern European member states of the EU [see (1, 2) for an overview of how the situation has evolved over time]. In some member states, such as Poland, the disease was limited to a small part of the country and not to the entire country (3). Because of the emergence of ASF in Eastern Europe, ASF is considered to pose a risk to both Eastern and Western European countries (4). In particular, as a route of spreading the disease, the wild boar has been of concern (5).

The member states and farming sector are concerned about the economic consequences caused by possible ASF outbreaks, measures to control and eradicate the disease, and market implications of the disease. The EU has adopted a common policy to control ASF. This policy includes measures such as the culling of susceptible animals, cleaning and disinfecting infected premises, and imposing restrictions on pig transports in surveillance and protection zones which are established around the infected premises (6). The restrictions on intra-community trade are however imposed on regional basis, which implies that not the entire country may face restrictions to trade within the EU when ASF is detected in the country (7). In addition, the European Commission may adopt acts taking exceptional support measures (such as financial support) for the affected market in order to take account of restrictions on trade as a result from the application of measures for combating the spread of diseases in animals (8), which implies that the market effects may be limited by support policies.

Scientific literature suggests that ASF outbreaks, even if they are small, can cause substantial economic losses to pig farming in the affected states [e.g., (9, 10)]. Because ASF poses a sanitary risk, countries have the right to prohibit imports of pigs and products of pig origin from the areas where ASF is or has been present (11). The impact of ASF on the international trade of pigs and products of pig origin is of particular interest, and ASF has been argued to reduce export quantity and the price of pigmeat in the country where it has been detected [e.g., (9, 10)]. In addition to animal health considerations, the effects that trade restrictions caused by ASF may have on exports of pig products and on producer prices in the domestic markets are a major reason why stakeholders are concerned about the risk of disease in the EU. However, while a highly contagious animal disease has the potential to cause substantial economic damage, the impacts of the disease can vary from country to country, and the characteristics of a country, such as export orientation and the level of development of the industry, may contribute to the impacts (12).

Especially in developed countries, economic impacts of a highly contagious animal disease are often studied ex-ante by using simulation models whereas ex-post studies are less common. There are a few examples where the market implications of a highly contagious animal disease have been studied by using econometric methods and time series data. For instance, Jarvis et al. (13) investigated beef prices in different markets and observed that foot and mouth disease (FMD) free producers enjoyed a higher price than producers from FMD-endemic countries. In addition, Wilson and Kinsella (14) studied the impact of FMD on the price of beef in the United Kingdom following the 2001 epidemic, and Barratt et al. (15) used a time series analysis to estimate the indirect costs of animal disease control strategies using a FMD outbreak in Scotland as a case study. There are several studies which have looked at the financial or economic impacts of other animal diseases ex-post. Such diseases include for instance porcine reproductive and respiratory syndrome (16), bovine spongiform encephalopathy (17), and bluetongue (18).

Although the economic consequences of ASF outbreaks and their control in Europe have been addressed in various countries [e.g., (10, 19–21)], the impact of the ASF epidemic in the Eastern European pigmeat market have not, according to the author's knowledge, been investigated retrospectively and therefore long-term impacts have not been verified. The epidemic that started in the EU in 2014 provides a good opportunity to quantify the effects of ASF on markets at country level, and the information could be utilized when considering policies and support measures to the pig farming sector. Hence, the objective of this study was to analyze how the ASF epidemic has contributed to the production, export, national pig inventory and prices of pigmeat in the EU member states where it was observed during the period 2010–2019.

MATERIALS AND METHODS

Model

The analysis included two steps. First, a descriptive analysis was conducted. The evolution of the price of pigmeat, annual production and export quantities of pigmeat, and the national pig inventory (the number of domestic pigs in the country) for a time period of 10 years were examined by using empirical data described in the next section. The period was selected so that it included several disease-free years for all countries expect Italy and provided information on ASF until the most recent year for which data were available. In addition, Pearson correlation coefficients were computed and presented to carry out a preliminary analysis of raw data.

Second, a set of four equations describing the effects of the number of infected wild boars, the number of ASF infected domestic pig farms, lagged values of market parameters and dummy variables to year-to-year change in the price of pigmeat, the annual production and export quantities of pigmeat, and the national pig inventory in the country were specified in a reduced form and estimated. Because of serial correlation issues, the dependent variables of equations were in first-differenced form as follows.

$$\Delta x_{i,t} = \alpha_i + \boldsymbol{\beta_i x_{t-1}} + \boldsymbol{\delta_i y_t} + \boldsymbol{\theta_i z_t} + \varepsilon_{i,t}$$

for i = {Price of pigmeat, Production quantity, Export quantity, Pig inventory} and where $\Delta x_{i,t} = x_{i,t} - x_{i,t-1}$; where t is the time index; $\Delta x_{i,t}$ represents the change in the natural logarithm (ln) of the dependent variable i from time t–1 to time t; i is the variable name index; $x_{i,t}$ represents the variable i (price of pigmeat, production quantity, export quantity or pig inventory) at the time period t; α_i is the intercept; $\boldsymbol{\beta_i}$, $\boldsymbol{\delta_i}$, and $\boldsymbol{\theta_i}$ are vectors of estimated parameters; $\mathbf{x_{t-1}}$ represents a vector of ln-transformed variables price of pigmeat, production quantity, export quantity and pig inventory in period t–1; $\mathbf{y_t}$ is a vector of dummy variables representing the year and country of observation; $\mathbf{z_t}$ is a vector representing six variables [the dummy variable that ASF has been observed in wild boar in the country, dummy variable that ASF has been observed in domestic pigs in the country, $ln(1 +$ number of new ASF positive pig farms in year $t)$, $ln(1 +$ number of new ASF positive pig farms in year t–1), $ln(1+$number of new ASF infected wild boars in year $t)$, $ln(1+$number of new ASF infected wild boars in year t-1)]; and $\varepsilon_{i,t}$ is an error term for the equation representing variable i.

The system of simultaneous equations was estimated by using seemingly unrelated regression equations (SURE) method (22). This method is suited for estimating equations which have a specific form of the variance-covariance matrix, i.e., equations in cases where the error terms of estimating equations are correlated. This can be the case when variables are determined simultaneously. For instance, the supply, demand and price of a

TABLE 1 | Number of outbreaks of with ASF in domestic pigs and in wild boar per country and per year in the European Union during years 2010–2019.

Year	Belgium	Bulgaria	Czech Republic	Estonia	Italy	Latvia	Lithuania	Hungary	Poland	Romania	Slovakia
Number of outbreaks in domestic pigs											
2010	0	0	0	0	9	0	0	0	0	0	0
2011	0	0	0	0	31	0	0	0	0	0	0
2012	0	0	0	0	74	0	0	0	0	0	0
2013	0	0	0	0	109	0	0	0	0	0	0
2014	0	0	0	0	40	32	6	0	2	0	0
2015	0	0	0	18	16	10	13	0	1	0	0
2016	0	0	0	6	23	3	19	0	20	0	0
2017	0	0	0	3	17	8	30	0	81	2	0
2018	0	1	0	0	10	10	51	0	109	1,163	0
2019	0	44	0	0	1	1	19	0	48	1,724	11
Number of outbreaks in wild boar											
2010	0	0	0	0	1	0	0	0	0	0	0
2011	0	0	0	0	3	0	0	0	0	0	0
2012	0	0	0	0	17	0	0	0	0	0	0
2013	0	0	0	0	67	0	0	0	0	0	0
2014	0	0	0	41	70	148	45	0	30	0	0
2015	0	0	0	723	46	753	111	0	53	0	0
2016	0	0	0	1,052	132	865	303	0	80	0	0
2017	0	0	202	637	93	947	1,328	0	741	0	0
2018	161	5	28	230	64	605	1,443	138	2,438	170	0
2019	482	165	0	80	60	369	464	1,598	2,468	683	27

Source: European Commission, Animal Disease Notification System (ADNS)[a].

[a]*An "outbreak" means the holding or place situated in the territory of the Community where animals are assembled and where one or more cases of ASF has or have been officially confirmed. For instance, in Estonia the number of reported cases of ASF in wild boar (26) has been larger than the number of outbreaks of ASF in wild boar.*

product are likely to be determined simultaneously and therefore the error terms of equations representing these can be correlated. The problem can be taken into account by using the SURE method [see, e.g., (23)].

The system of four equations was estimated in a single iterative model run. Due to the model structure explained above, country-specific levels were considered as random effects whereas country-specific trend and year-specific effects were considered as fixed effects. Annual dummy variables also implicitly included the effects of events such as ASF outbreak in Asia. The estimation procedure was initiated by including all explanatory variables in each of the four simultaneous estimation equations. However, in the final model only variables which were statistically significant at a risk level of 5% were included. The variables were excluded from the model stepwise by dropping the least significant variable ($p > 0.05$) from each equation after each estimation round, and then re-estimating the system of equations until all the variables remaining in the model were statistically significant at a risk level of 5%. The estimations were conducted with an econometrics toolbox (24) in Matlab R2014b (The MathWorks Inc., Natick, Massachusetts).

Data

The data included annual market information on producer prices, production, and volume of export of pigmeat as well as the number of pigs (the national pig inventory) in ten EU member states where ASF had been reported between 2010 and 2019 (Belgium, Bulgaria, the Czech Republic, Estonia, Italy, Latvia, Lithuania, Hungary, Poland, Romania, and Slovakia). In addition, data for Germany and Denmark were illustrated in the descriptive analysis to provide information from major pig producing countries, which did not have an ASF outbreak during the study period. The data were obtained from publicly available statistics and records. Information on the number of ASF cases detected in each country in each year was retrieved from the European Commission Animal Disease Notification System (25). While ASF has been endemic in the island of Sardinia in Italy, in other countries it was introduced during 2014 through to 2019. The largest number of ASF cases had been observed in Poland, Romania, Italy and the Baltic countries (**Table 1**).

The annual prices of pigmeat (class E) were retrieved from the European Commission (27). The export quantities of pigmeat, the quantity of pigmeat produced and the pig inventory (all domestic pigs in the country), were obtained from the Eurostat database (28). These exports included all fresh, frozen, cured, smoked and other pigmeat, and other products specified as pig product in the combined nomenclature CN8 categories starting with CN02 or CN15; but it did not include preparations which contained other meat besides pigmeat. Quantitative variables were converted to an index so that the base year for each country was 2010 (=100), the purpose of which was to reduce the scale

TABLE 2 | Mean and standard deviation of parameters used in the seemingly unrelated regression equations estimation.

Variable	Mean	Standard deviation
Change in ln(Production quantity of pigmeat) from year $t-1$ to year t	0.019	0.086
Change in *ln*(Price of pigmeat) from year t–1 to year t	0.020	0.109
Change in *ln*(National pig inventory) from year t–1 to year t	−0.025	0.065
Change in *ln*(Export quantity index of pigmeat) from year t–1 to year t	0.036	0.278
Intercept	1.000	0.000
Dummy variable, 1 if year 2012; otherwise 0	0.111	0.316
Dummy variable, 1 if year 2013; otherwise 0	0.111	0.316
Dummy variable, 1 if year 2014; otherwise 0	0.111	0.316
Dummy variable, 1 if year 2015; otherwise 0	0.111	0.316
Dummy variable, 1 if year 2016; otherwise 0	0.111	0.316
Dummy variable, 1 if year 2017; otherwise 0	0.111	0.316
Dummy variable, 1 if year 2018; otherwise 0	0.111	0.316
Dummy variable, 1 if year 2019; otherwise 0	0.111	0.316
Dummy variable, 1 for Bulgaria, otherwise 0	0.091	0.289
Dummy variable, 1 for the Czech Republic, otherwise 0	0.091	0.289
Dummy variable, 1 for Estonia, otherwise 0	0.091	0.289
Dummy variable, 1 for Italy, otherwise 0	0.091	0.289
Dummy variable, 1 for Latvia, otherwise 0	0.091	0.289
Dummy variable, 1 for Lithuania, otherwise 0	0.091	0.289
Dummy variable, 1 for Hungary, otherwise 0	0.091	0.289
Dummy variable, 1 for Poland, otherwise 0	0.091	0.289
Dummy variable, 1 for Romania, otherwise 0	0.091	0.289
Dummy variable, 1 for Slovakia, otherwise 0	0.091	0.289
Dummy variable, 1 if ASF reported in the country in t, otherwise 0	0.455	0.501
ln(Price of pigmeat, year t–1)	5.045	0.120
ln(Production quantity index for pigmeat, year t–1)	4.662	0.230
ln(National pig inventory, year t–1)	4.484	0.111
ln(Quantity index for exported pigmeat, year t–1)	4.910	0.488
ln(1+number of new ASF positive pig farms, year t–1)	0.866	1.518
ln(1+number of new ASF cases in wild boat, year t–1)	1.7408	2.5726
ln(1+number of new ASF positive pig farms, year t)	1.0649	1.7016
ln(1+number of new ASF cases in wild boat, year t)	2.309	2.790

effect in some cases. However, the characteristics of the countries were taken into account by the inclusion of country-specific dummy variables. For estimation purposes, continuous variables were ln-transformed. Means and the standard deviations of variables used in the seemingly unrelated regression equations estimation are presented in **Table 2**.

RESULTS

Descriptive Analysis

The data indicated that the pig sector has evolved differently in countries where ASF has been detected during the past few years (**Figure 1**). In some countries, such as Bulgaria and Latvia, there has been a clear increasing trend in the production quantity while in some other countries, such as the Czech Republic, the production has decreased during the past decade. The national pig inventory in general had decreased in all ten countries, which is likely associated with the increased productivity of pig farming. There was a clear decrease in the national pig inventory especially in Lithuania. The development of producer price of pigmeat and the quantity of exported pigmeat over the decade varied from year to year in most countries. The quantity of exports from Romania was not included in the Figure because of large differences between the years. The quantity of pigmeat exported from Romania increased up to index value 426 by year 2012 (2010 = 100) and further to the value 883 in 2017, but thereafter the export index decreased to 553 in 2018 and to 179 in 2019. However, the initial amount of pigmeat exported from Romania was low [for further information on pig sector in Romania, please see Popescu (29)]. In addition, Poland had increased exports at the end of the decade when compared to year 2014 (**Figure 1**).

When considering the changes from 2013 to 2015, i.e., from the year before the major ASF epidemic started in Eastern Europe until the second year of the epidemic in each country where ASF had been observed in 2014, the national pig inventory decreased in all four countries where ASF was introduced (Estonia −15.1%, Latvia −9.1%, Lithuania −8.9%, Poland −3.7%). These changes were larger and more negative than in most other countries in the data for the same period. In these other countries, the change (from 2013 to 2015) ranged from +4.0% in Hungary to −0.6% in Slovakia, and Romania was an outlier in this group of countries with a change of −4.9%. Changes observed in the pig inventory between 2017 and 2019, when ASF was introduced into Czech Republic, Romania, Belgium, Bulgaria, Hungary, and Slovakia, varied by country.

From 2013 to 2015, a clear increase in the quantity of produced pigmeat was observed in three of four countries where ASF had been introduced in 2014 (Estonia +14.9%, Latvia +11.9%, Poland +13.2%). Also three countries where ASF had not occurred, showed an increase in production volumes during the same period (Bulgaria +16.6%, Hungary +21.6%, Romania +7.1%). The remaining countries (Belgium, Czech Republic, Italy, Lithuania) witnessed a decrease in production quantity. However, in a descriptive analysis it remained unclear what the contribution of ASF to these changes was. The quantity of exported pigmeat varied from year to year and country to country. From 2013 to 2015, Estonia (−17.9%), Latvia (−41.3%), Lithuania (−19.9%) and Poland (−6.5%) all faced a decrease in the quantity of exported pigmeat. In these countries ASF had been introduced in 2014. However, four other countries had also faced a decrease (ranging from −0.1 to −34%) in pigmeat exports during the same time period. Of those countries where ASF had been introduced in 2017 or 2018, the export quantities in the year after the introduction of ASF into the country were lower than export quantities in the year before the introduction of ASF (Belgium −1.6%, the Czech Republic −24.0%, Hungary −0.3%, Romania −79.7%). In other countries, the changes in the exports during the same period were in the range of −18.9 to +37.1% (**Figure 2**).

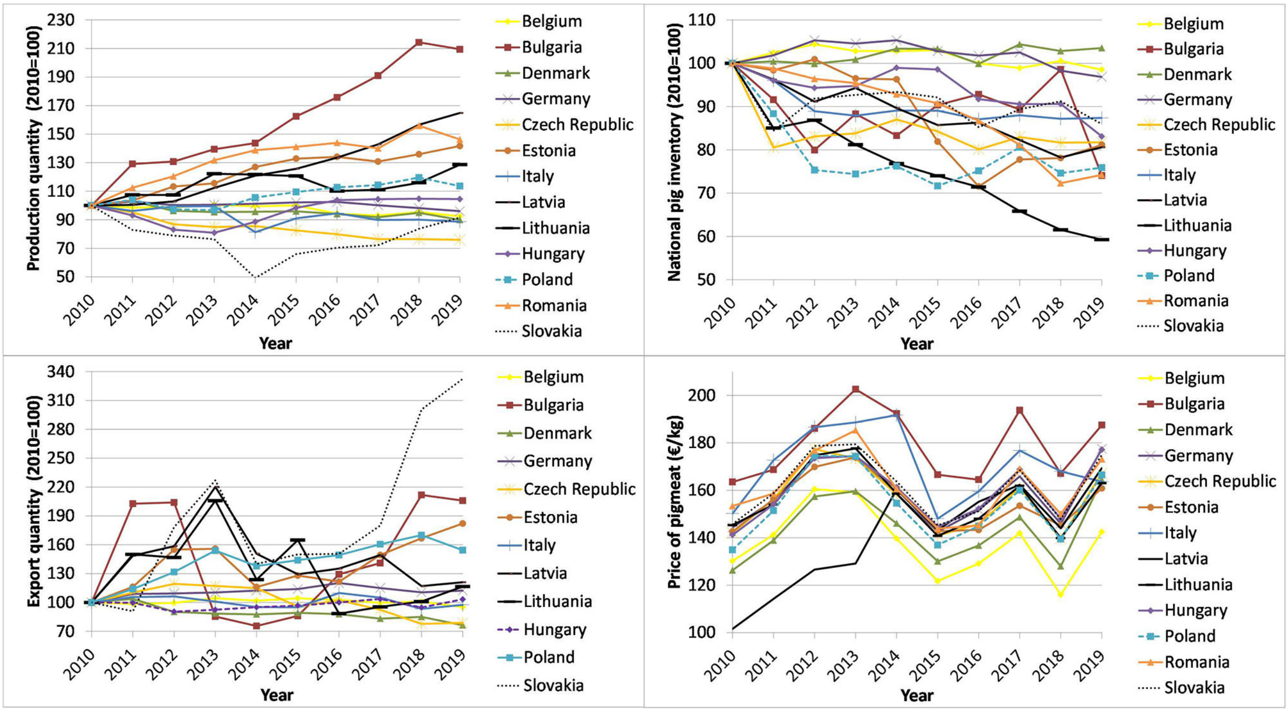

FIGURE 1 | The evolution of the quantity of pigmeat produced, the national pig inventory, the quantity of exported pigmeat (2010 = 100), and the price of pigmeat (class E, €/kg) in the study countries and in Germany and Denmark. Romania was not included in the export graph because of visualization reasons. Sources: Eurostat, the European Commission.

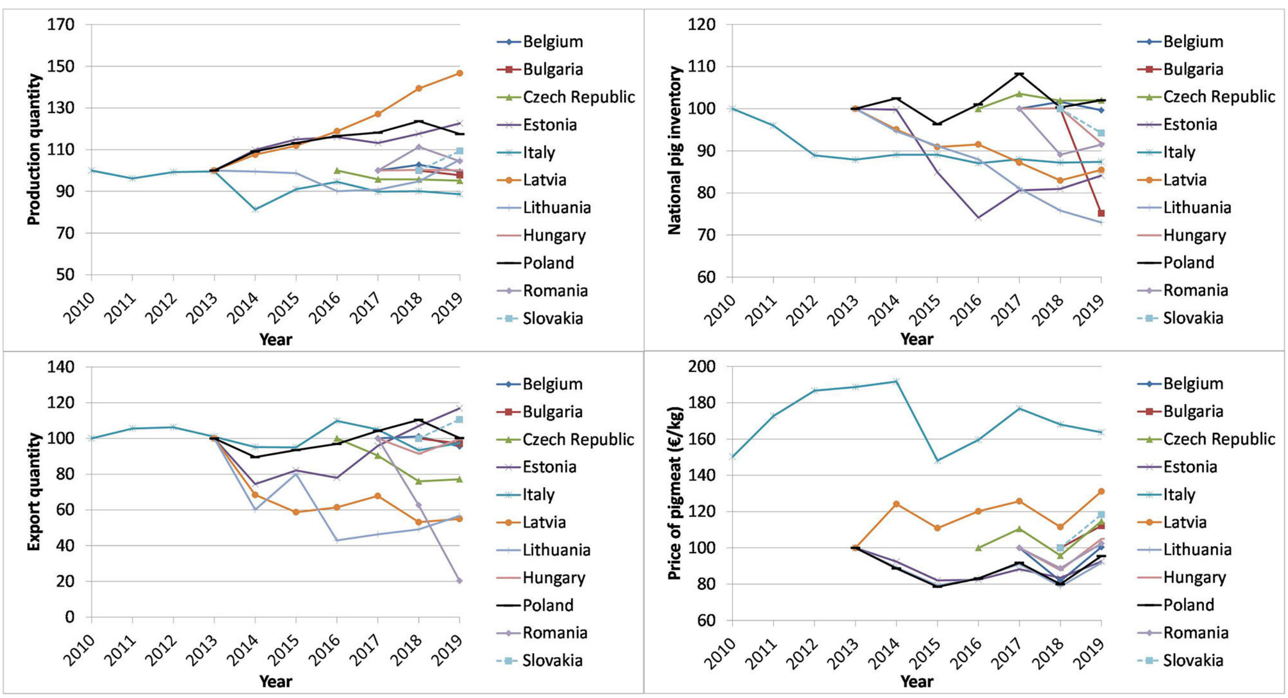

FIGURE 2 | The evolution of the quantity of pigmeat produced, the national pig inventory, the quantity of exported pigmeat (value in the year before ASF was observed in the country = 100), and the price of pigmeat (class E, €/kg) in the study countries starting from the year before ASF was observed in each country. Sources: Eurostat, the European Commission.

TABLE 3 | Pearson correlation coefficients (upper triangle, in roman style) and their *p*-values (lower triangle, in italics) of market parameters and the number of ASF outbreaks in the country.

Variable	Production quantity index	Pig inventory index	Export quantity index	Price for pigmeat	Ln of number of ASF outbreaks, domestic pigs	Ln of number of ASF outbreaks, wild boar
Production quantity index	**1**	0.105	0.090	**−0.192**	0.112	−0.020
National pig inventory index	*0.201*	**1**	**0.413**	**−0.202**	**0.176**	0.059
Export quantity index	*0.274*	*<0.001*	**1**	**−0.262**	**0.308**	**0.353**
Price for pigmeat	*0.019*	*0.013*	*<0.001*	**1**	**−0.542**	**−0.623**
Ln of number of ASF outbreaks, domestic pigs	*0.174*	*0.032*	*<0.001*	*<0.001*	**1**	**0.725**
Ln of number of ASF outbreaks, wild boar	*0.813*	*0.472*	*<0.001*	*<0.001*	*<0.001*	**1**

Correlation coefficient in bold are statistically significant at 5% risk level.

Overall, the price of pigmeat evolved quite similarly during the study period in all other countries except in Latvia, where the price development of class E pigmeat deviated from the generic EU price development after 2013 and increased overall by 67% during the decade (**Figure 1**). During 2013–2015, the producer price of class E pigmeat decreased by 17.8–23.5% in all other countries except Latvia, where the price increased by 10.9%.

Table 3 shows Pearson correlation coefficients for indices representing production and export quantities and the number of pigs, the price of pigmeat and the number of ASF cases in the country. Most correlations were statistically significant and it is likely that also the equations representing the evolution of these parameters have correlated error terms. The price of pigmeat correlated negatively with all other parameters. Statistically significant correlations between parameters other than the price of pigmeat were positive.

Estimation Results

According to the estimation results, the models explained altogether about 71% of the variation in the system of equations. The coefficient of determination for the price of the pigmeat equation was 85%. For other equations, this ranged from 43 to 48%. The error terms of four equations were correlated and these correlations were statistically significant. The cross-equation correlation was negative between the price of pigmeat and the export quantity equations. Other cross-equation correlations were positive. The largest cross-equation correlations were observed between the export quantity and the production quantity equation and the export quantity and the price equation.

An increase in the number of farms with ASF infection in a given year was associated with a decreased pig inventory and an increased production quantity in the same year. Moreover, this was associated with a decrease in both production quantity and exports in the next year. This observation was in line with the observations made from the raw data. An increase in the number of ASF outbreaks in wild boar in a given year was associated with an increase in the price of pig meat and a decrease in the national pig inventory in the next year (**Table 4**, **Figure 3**).

Some of the lagged variables representing the national pig inventory, quantity of pigmeat produced, quantity of pigmeat exported, or the price of pigmeat contributed to year-to-year changes in these variables. An increase in the producer price of pigmeat in a given year was related to a decrease in the price of pigmeat and to a decrease in the quantity supplied in the next year. An increase in the production quantity in a given year was related to a lowered production quantity and national pig inventory in the next year, and also to an increase in the producer price of pigmeat in the next year. An increase in the national inventory in the current year was associated with a decrease in the national pig inventory in the next year and an increase in export quantity in the next year. Finally, an increase in the exports of the current year was associated with a decrease in the quantity of exports in the next year (**Table 4**, **Figure 3**).

Several dummy variables representing years were significant in explaining any annual changes in the price of pigmeat and production quantity. Country-specific dummy variables were statistically significant especially in equations which represented production and export quantities.

DISCUSSION

The results indicate that the consequences of ASF to pigmeat markets in a country where ASF has been introduced are complex and confounded by possible interrelated and country-specific factors. Moreover, the estimation results suggest that the pigmeat markets can respond differently to the introduction of ASF into the country. The results suggest that on average, when taking into account the size of an outbreak, the new cases of ASF reduced pigmeat exports by close to 15% in the year after the cases had occurred, production quantity by more than 4%, and national pig inventory by 3–4% both in the current and the next year. The larger impact on exports is in line with the literature [e.g., (9–11, 30)].

The magnitude of impacts is affected by the size of epidemic. The larger and the more widespread the disease is, the larger can its impact expected to be. This is logical because also the policy measures (7) to combat ASF are context-specific. Stochastic simulation models [e.g., (10, 19)] have shown that the market effects of ASF, which are comprised of changes in prices and quantities traded, can vary substantially from

TABLE 4 | Estimation results for a system of four simultaneous equations describing annual change in the logarithm of the national pig inventory, quantity of pigmeat produced, quantity of pigmeat exported and the price of pigmeat (class E).

	Production quantity		Price of pigmeat		Pig inventory		Export quantity	
	Estimate	***p*-value**	**Estimate**	***p*-value**	**Estimate**	***p*-value**	**Estimate**	***p*-value**
Intercept			1.519	< 0.001	3.215	< 0.001		
Dummy variable for year 2012	−0.068	0.0005	0.049	0.001				
Dummy variable for year 2013	−0.062	0.0028						
Dummy variable for year 2014	−0.094	< 0.001	−0.086	< 0.001				
Dummy variable for year 2015			−0.183	< 0.001				
Dummy variable for year 2016			−0.073	< 0.001				
Dummy variable for year 2018			−0.187	< 0.001				
Dummy variable for Bulgaria	0.133	< 0.001	0.047	0.018			0.218	0.009
Dummy variable for the Czech Republic	−0.142	< 0.001	0.056	0.002	−0.104	< 0.001		
Dummy variable for Estonia	0.067	0.007					0.264	0.002
Dummy variable for Italy	−0.112	< 0.001	0.060	0.002			0.228	0.025
Dummy variable for Latvia	0.127	< 0.001					0.275	0.002
Dummy variable for Lithuania					−0.118	< 0.001	0.285	0.001
Dummy variable for Hungary	−0.066	0.007	0.059	0.001				
Dummy variable for Poland					−0.086	< 0.001	0.397	< 0.001
Dummy variable for Romania	0.070	0.005					0.800	< 0.001
Dummy variable for Slovakia	−0.182	< 0.001	0.090	< 0.001	−0.076	0.001	0.358	< 0.001
ln(Price of pigmeat, *t*–1)	0.356	< 0.001	−0.400	< 0.001				
ln(Index of supplied quantity, *t*–1)	−0.374	< 0.001	0.114	0.001	−0.126	< 0.001		
ln(Index of national pig inventory, *t*–1)					−0.579	< 0.001	0.447	< 0.001
ln(Index of quantity of exports, *t*–1)							−0.442	< 0.001
ln(1+number of new ASF infected farms in *t*–1)	−0.018	0.021					−0.061	0.001
ln(1+number of new ASF infected wild boars in *t*–1)			0.0061	0.003	−0.007	0.009		
ln(1+number of new ASF infected farms in *t*)	0.016	0.009			−0.011	0.003		

Equation system R^2		0.706		
Equation R^2	0.476	0.854	0.430	0.428
Equation R^2 adjusted	0.389	0.832	0.379	0.363

	Production quantity	**Price index**	**Number of pigs**	**Export quantity**
Cross-equation correlations				
Production quantity	1.000	0.095	0.011	0.424
Price index of pigmeat	0.095	0.019	0.019	−0.189
Number of pigs in the country	0.011	0.019	1.000	0.043
Export quantity of pigmeat	0.424	−0.189	0.043	1.000

	Production quantity	**Price index**	**Number of pigs**	**Export quantity**
Cross-equation significance estimates				
Production quantity	0.004	0.000	0.000	0.005
Price index of pigmeat	0.000	0.002	0.000	−0.002
Number of pigs in the country	0.000	0.000	0.002	0.000
Export quantity of pigmeat	0.005	−0.002	0.000	0.044

case to case. For instance, Halasa et al. (19) found in a simulation carried out for Denmark that export losses caused by ASF varied between €250 and €383 million per epidemic. These studies also suggest that export losses play a larger role in the total losses than direct costs associated with disease control measures.

As it has been illustrated in previous studies for different diseases [e.g. (31)], an outbreak of a disease such as ASF can lead to a supply shock and a demand shock. The latter is usually associated with decreasing exports when countries prohibit the imports of pig products originating from the region or country where ASF occurs. In practice, the effects of these shocks depend

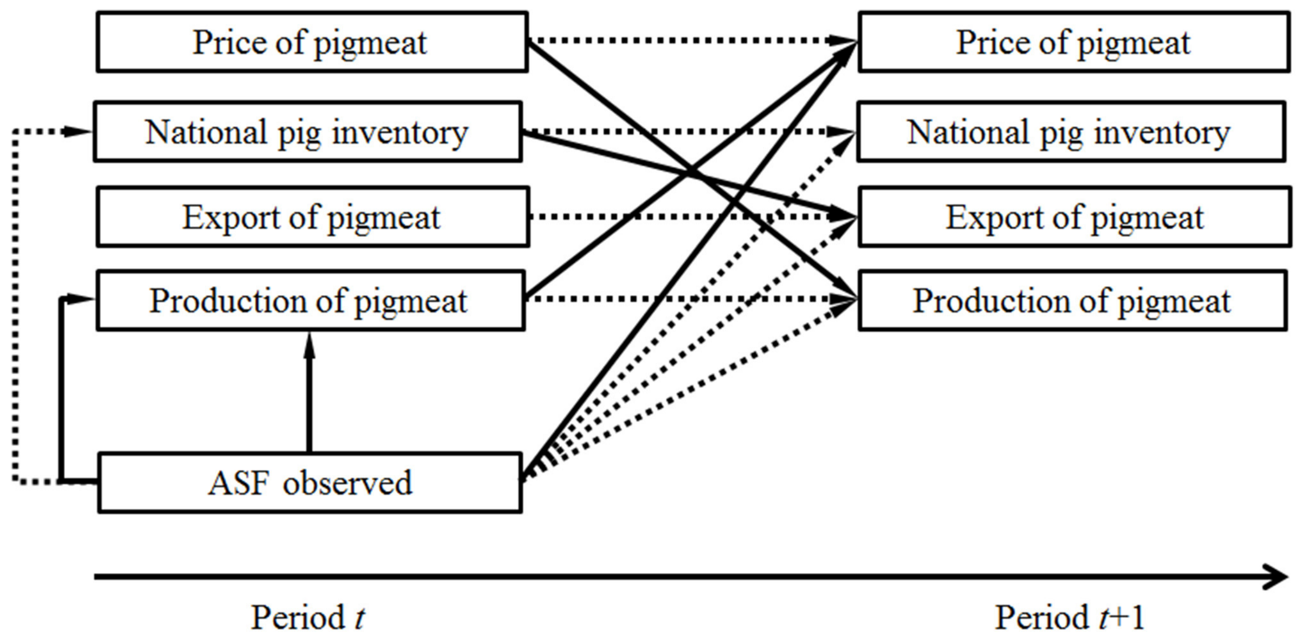

FIGURE 3 | An illustration of the main effects of variables (presented in boxes) according to the estimated system of equations in two time periods [*t* (on the left) and *t*+1 (on the right)]. Dashed lines represent a negative association (an increase in one variable is associated with a decrease in another variable) and solid lines represent a positive association (an increase in one variable is associated with an increase in another variable). Observed cases of ASF in domestic pigs or wild boar are associated with variables in four uppermost boxes in the present period *t*. These all may be associated with variables on the right-hand in the next period (*t*+1).

on factors such as the size and duration of epidemic and reactions of trade partners. While changes in export quantities estimated in the present study were larger than those of production or prices, it is to be noticed that the market losses are comprised of the net effect of changes in both the price and quantity traded and these changes can take place over a longer time period. Another factor which may influence the magnitude of market losses suffered by the pig sector is disease control policy. For instance, Halasa et al. (9) found that increasing testing of dead animals in the protection and surveillance zones reduced both the duration of epidemic and economic losses caused by ASF.

This study attempted to assess the magnitude of the market components of outbreak by using data from actual ASF epidemics. The results suggest that an ASF outbreak can reduce the production of pigmeat, export quantities, and the national pig inventory (i.e., "production capacity") in the short and medium term. Particularly, the decrease in the national pig inventory can be expected because of disease control and eradication measures. However, the production of pigmeat shortly after observing ASF in a country can even increase as a consequence of an ASF outbreak. One possible explanation for this is that farmers may perceive business prospects becoming less favorable and therefore they may begin culling animals, which may lead to slightly increased supply in the very short run and a reduced pig inventory. Moreover, restrictions imposed on farms in the protection and surveillance zones may raise slaughter weights and thus increase the supply locally after the restrictions are removed. Changes in the supply, national pig inventory, and exports of pigmeat can be expected to occur with a delay when the disease starts influencing the production capacity and export markets.

Although the price development over time is driven by global market developments, ASF outbreaks do impact local producer prices. A decrease in the producer price during the epidemic and an increase after the disease has been eradicated has been observed previously in simulation-based studies [e.g., (30, 32, 33)]. However, the present data did not suggest a substantial instantaneous drop in pigmeat price, which has been postulated in cases representing both ASF and other highly contagious animal diseases [e.g., (10, 14, 19, 34)]. This may be because of the EU policies to limit intra-community trade on a regional basis (7). The possibility for exceptional support measures (8) may also have relieved the impacts in the countries which were affected by ASF. In qualitative analysis, countries where ASF was introduced in 2014 did not face a development that was different from the other countries in the data. This may be related to the restrictions imposed by Russia on pigmeat of EU-origin, which—it has been argued—were an important reason for the decreasing price of pigmeat in the EU in 2014–2015. It may also be related to the afore-mentioned EU policies. Moreover, if the supply of meat in the region where a disease is present is reduced, then other regions which have not suffered from the disease can, in some cases, benefit from the outbreak, and these other regions may even increase their supply of pigmeat. Mangen and Burrell (30) have illustrated such a case at the national scale for classical swine fever, and Mason-D'Croz et al. (35) in the global context for ASF. Taking into account such differences within the country may smooth the effects at the country level. These aspects suggest that from the perspective of pig sector, it is essential to keep the restrictions on trade as limited as possible.

The country-specific price development appeared to be related to the EU-level price development. The development in Latvia may be associated with the fact that the price of pigmeat in the country was initially 20–38% lower than in any other member state included in the data in the same year. The dependent variables in the system of equations were in a first-differenced form, which together with the development of variables implied that there were significant country-level development trends in each of the four equations, and in addition, a general trend in the price and pig inventory equations (i.e., the intercept).

There are also other market considerations which are relevant to the market implications of ASF. For instance, it has been found that the farm gate price of beef in the UK decreased and retail price increased, and the average marketing margin of beef (retail price minus farm gate price) increased by 3.1% following the FMD outbreak when compared with the pre-FMD period (14). The present study did not consider the possibility that ASF would affect consumer preferences. Although this may be highly relevant in the event of some other diseases [such as zoonotic diseases or production diseases; see, e.g., (36) for discussion], in the event of ASF it is unlikely because ASF does not pose a risk to human health.

Meat markets may respond to disease events sluggishly and in different ways. The present result that the impact of the ASF variable on the price of pigmeat was positive can be related to reduced supply, which has been also observed in simulation-based studies. The results suggest that a reduced supply and production capacity (the national pig inventory) as a consequence of ASF can contribute to changes in pigmeat prices. Moreover, the markets may show stronger price impacts in the very short term than at an annual level, and these short-term impacts may be over-represented in public discussion. Regions where the disease has not been detected may also increase their supply and compensate for the loss of production in areas where the disease is present, as illustrated by previous studies (30, 35), and this may smooth out the markets effects of ASF at the country level.

Besides Europe, ASF was spreading in China and some other countries in Asia during 2018–2019. The epidemic in China, the largest pigmeat producer country in the world, has been estimated to impact both Chinese and global pigmeat markets. Although the effect of the Chinese epidemic on the pigmeat market was not considered explicitly in the present model, yearly dummy variables captured the overall effects of unspecified annual changes in the dependent variables, including the effects of ASF in Asia to the European pigmeat markets. However, such dummy variables cannot separate the effect of an individual event, such as ASF epidemic in China, from the effects of other unspecified events occurring in the same year. Mason-D'Croz et al. (35) projected that global pork prices could increase by 17–85% as a consequence of ASF epidemic in China. Recent EU agricultural markets outlook (37) also showed that the ASF situation in China will impact the price of pigmeat in the EU, and that the faster Chinese production will recover from ASF, the lower are prices in the EU and China forecast to be in the coming years.

The dynamics of supply, exports prices and pig inventory can play an important role in determining the impacts of ASF in the domestic pigmeat markets. While one can argue that the introduction of ASF into the country leads to a falling producer price of pigmeat, this may not be the full picture. ASF may lead to a decreasing pig inventory, supply and export of pig meat. This contributes to the balance between the supply and demand for pig meat in the domestic markets by decreasing the supply and subsequently exports may also decrease pigmeat. Hence, the market may not show large price reductions because reductions in supply can partly compensate for the effects of excess local supply in cases where some of the export markets become temporarily closed. In addition, export orientation of the country may also play a role in determining the impacts. Because EU policies can limit disruptions in the intra-community trade to only regions where the measures are limited (7), but third countries may apply the restrictions to the entire country, this may shift some pigmeat exports of an infected country from the third-country markets to the common market.

Caution must be taken when interpreting these results, because a reduced form model was estimated and the inclusion or exclusion of variables in the model may have an effect on the result. Including additional structures in further analyses to explain the market developments could clarify the results. These results also suggested that there are important country-specific trends, which must be controlled properly in the estimation. In addition, the effects of wider market shocks, such as the Russian embargo on importing pig products from the EU and a generic fall in the producer price of pigmeat, which may be a confounding factor in European markets in 2014–2015, and 2018–2019 events in the global pigmeat markets (especially ASF in China), must be controlled. In the current study they were taken into account by annual dummy variables. The ASF-affected time period available at the time of the study covered only a few years and not all effects may have been observable during the study period. Topics for further research, which were not examined in the present analysis, could conclude impacts of diseases on the exports of meat preparations such as ready-to-eat meals and regional differences within countries where a highly contagious animal disease has been observed.

CONCLUSION

In conclusion, an ASF outbreak can influence the pigmeat markets adversely and these effects vary from country to country. An outbreak reduces the supply of pigmeat, exports and national pig inventory in the short term or in the longer term. The effects on pigmeat exports are likely to be stronger than the effects on production and prices, and the main effects may occur with a delay after the meat industry has used up the capacity to adjust the supply. The effects of ASF on market prices are complex, and decreasing supplies and exports can relax supply side pressures on the markets. The market effects of an ASF outbreak on the pig production sector is a combination of changes in prices, supply and trade, and these effects can change over time. When permitted by epidemiological situation, stakeholders are encouraged to promote the flexibility of the markets by limiting the market disruptions to the minimum, because flexibility of trade can help to reroute trade flows and mitigate the negative effects of ASF to the pig sector.

DATA AVAILABILITY STATEMENT

The datasets for this study can be found in the websites of Eurostat and European commission (see references), or are available from the author upon request.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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Variable Cognition in ABM Decision-Making: An Application to Livestock Vaccine Choice

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Modeling realistic human decision-making is an important feature of good policy design processes. The use of an agent-based modeling framework allows for quantitative human decision-models that assume fully rational agents. This research introduces a dynamic human decision-making sub-model. The parameterisation of human memory and "rationality" in a decision-making model represents an important extension of decision-making in ABMs. A data driven model of herd movement within a dynamic natural environment is the context for evaluating the cognitive decision-making model. The natural and human environments are linked via memory and rationality that affect herdsmen decision-making to vaccinate cattle using a once-for-life vaccine (Rift Valley fever) and an annual booster vaccine (Contagious Bovine Pleuropneumonia). The simulation model uses environmental data from Samburu county, Kenya from 2004 to 2015. The cognitive parameters of memory and "rationality" are shown to successfully differentiate between vaccination decisions that are characterized by annual and once-for-life choices. The preliminary specifications and findings from the dynamic cognition–pastoralist agent-based model (*PastoralScape*) indicate that the model offers much to livestock vaccination modeling among small-scale herders.

Keywords: cognition, pastoralist, decision-making, vaccine, agent-base model, Kenya

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INTRODUCTION

The economic sustainability of traditional pastoralist modes of livestock management is threatened by environmental, political and cultural forces across East Africa (1, 2). The increased frequency of droughts in East Africa over the past 20-years has sorely tested the resilience of livestock dependent communities in the region (3, 4). The need to model the complex interaction between natural and human system, as they affect livestock, is a research topic deserving further attention (5). The role of human decision-making as it affects livestock health adds to the complexity of such systems.

The advent of behavioral economics, and the acknowledgment within economics that human decision-making is more heterogeneous than previously assumed, leads one to question the oft assumed "rational agent" hypothesis. A review of decision-making paradigms used in animal health demonstrates the wide use of qualitative and quantitative decision frameworks (6). Within a quantitative framework, Prospect Theory is a common means of identifying heterogeneous methods of decision-making (7, 8). The use of short-term measures of human cognition is another (Choi and Iles, under review). Empirical investigation of the role of short-term cognitive capacity on human decision-making is based on the Mullainathan and Shafir's (9) "scarcity thesis". This thesis argues that financial stress affects human decision-making via changes in short-term cognition [(9, 10); (Iles et al., under review)].

Modeling realistic human decision-making is no less important with respect to animal health related decisions (6). However, the allure and utility of assuming fully rational agents remains strong. Constrained maximization/minimization approaches are limited in their ability to approximate the heterogeneity in human decision-making, necessary for good public policy modeling (11, 12). Whether simulation, Randomized Control Trials, or hypothetical scenarios are used to generate data, the fully rational agent is frequently assumed (13–16). This assumption of optimal decision-making is often demonstrated to be often unrealistic in the case of livestock management among the global poor (17).

Agent or individual-based modeling (ABM) provides a tractable means of analyzing the effects of interconnected dynamics of human and natural environments on household decision-making and resource allocation. Such a modeling framework allows for quantitative human decision-models that do not assume fully rational agents. Existing ABMs concerned with the dynamic environments of pastoralists in East Africa are typically concerned with tribal conflict (18, 19), decision-making (20), humanitarian crises (21), risk-sharing and cooperation (22–24), and climate change adaptation (25). While the present research also uses an ABM framework, its primary contribution is the introduction of a dynamic human decision-making sub-model. The parameterization of human memory and "rationality" in a decision-making model represents an important extension of decision-making in ABMs. The preliminary *PastoralScape* model presented here also provides insight into possible policy relevant extensions.

The current *PastoralScape* ABM documents a data driven model of herd movement within a dynamic natural environment. The natural and human environments are linked via memory and rationality that affect herdsmen decision-making to vaccinate cattle for Rift Valley Fever (RVF) and Contagious Bovine Pleuropneumonia (CBPP). The simulation model uses environmental data from Samburu county, Kenya, from 2004 to 2015. The difference in the frequency of vaccinations for each disease provides a means for assessing the effects of memory and "rationality" on one-time and repeated decision-making. Toward this end, the ABM introduces a Random Field Ising Model (RFIM) to estimate the binary choice to vaccinate. Such a decision is modeled in the context of the uncertainty of disease transmission dynamics of each disease.

MATERIALS AND METHODS

This section is organized using the Overview, Design Concepts and Details (ODD) structure for reporting ABMs (26). This reporting structure aims to provide a consistent format in reporting the objectives, structure and data used. In light of the need to more adequately capture the details of human decision-making, a revision to this protocol was proposed and referred to as ODD+D (27). The addition of the "+D" represents the addition of human decision making within the ABM. As a means of reporting the use of a RFIM in our model, where feasible, we follow the OOD+D protocol.

Overview

Purpose

The current preliminary *PastoralScape* simulation model aims to assess the medium-run dynamics of livestock vaccine decisions for two livestock diseases (RVF and CBPP). Pastoralist heads-of-households in Samburu county, Kenya, are assumed to have varying levels of cognitive ability. The medium-run is defined as an eleven-year period. For the purposes of clearly communicating the innovative human decision making sub-model, along with its interaction with the other sub-models, the livelihoods of human agents are simplified. All heads-of-households solely practice pastoralist cattle raising, cattle are not sold or traded, and there is no income within the model. Heads-of-households only make decisions related to livestock vaccination. Herdsmen only makes decisions about the movement of herds. Future development of the *PastoralScape* model will include a local economy and more diversified streams of household income.

The preliminary model assumes that all heads-of-households are homogenous. As a result, their utility functions, that drive their vaccine decision making, are fixed across agents. This assumption is made in order to clearly communicate the decision making sub-model and document the basic interactions between sub-models. While the *PastoralScape* model will ultimately enable the modeling of heterogeneous agents, the current version of the model is not designed to do so. Nevertheless, the innovativeness of the human decision making sub-model in the ABM readily allows for heterogeneity.

The use of RVF and CBPP as examples for modeling human vaccination decision-making provides two separate decisions that involve contrasting frequency and assumed levels of disease risk. Uncertainty is an important feature that drives decision-making (7, 8). The RVF vaccine's efficacy is once-for-life, administered to protect against sporadic outbreaks reported across Kenya. CBPP requires an annual booster with efficacy of approximately 6-months. The differing patterns of decision-making for these vaccines are assumed to influence vaccination outcomes. Outbreaks of RVF are closely linked to precipitation and mosquito populations (28–30). As a result, expectation of RVF outbreaks may follow a medium and long-run cyclical pattern. On the other hand, outbreaks of CBPP are less clearly predicted. Therefore, the assumed levels of uncertainty associated with disease outbreaks also differ between the two livestock diseases. No recent outbreaks of RVF in Samburu county have been recorded. The county maintains surveillance of CBPP despite the absence of a recent outbreak (31).

Entities, State Variables, and Scales

Three types of agents are modeled. These are: (a) heads-of-household, (b) cattle, and (c) herdsman. It is assumed that all heads-of-households engage in small-scale pastoralist cattle raising. There are no sedentary crop farmers or cattle rangers in the model. In keeping with the cultural practices of pastoralists in Samburu county, Kenya, each head-of-household has a herdsman to manage cattle. Culturally, these herdsmen are young men. Each agent type is defined by a set of attributes. Heads-of-households are defined according to the parameters of the RFIM and only make decisions as to whether to vaccinate livestock. These parameters include: memory (μ), degree of rationality (β), latent willingness to make a vaccination decision (f_i), access to public information [F(t)], and a social network (see Design Concept section for further details of the RFIM). Cattle are defined by: (i) sex, (ii) age, (iii) health, (iv) SIRV disease state, and (v) location. Cattle are modeled as individual agents, not as a single herd. Herdsmen are defined by (i) their co-location with livestock and their movement, and (ii) their knowledge of foraging conditions within a limited radius. Cattle and herdsmen are able to move spatially, while heads-of-households are fixed and uniformly distributed between five village locations.

The time-step used to progress the changes in the simulation environment, movement of livestock, and human decisions is 7 days. The time-step of the SIRV sub-model is scaled from daily. Environmental data (including Normalized Difference Vegetation Index (NDVI), Foraging Condition Index and precipitation measurement) are assumed constant during each month.

Design Concepts

Basic Principles

The coupling of natural and human environments in this ABM provides an important set of relationships that drive assumed changes in financial and mental stress of pastoralist households. The parameterisation of head-of-household memory and "rationality" provides flexibility to model two important aspects of cognitive ability (32–34). Human cognitive ability or capacity are believed to change over time due to stress, anxiety and the perception of these (10, 35, 36). According to Mullainathan and Shafir's "scarcity thesis," perceptions of household financial stress act as a tax on cognitive capacity [(9); (Iles et al., under review)]. Therefore, the parameterisation of two aspects of human cognition allows for more realistic modeling of the cognitive dynamics in discrete decision-making. Although the calibration of empirical data capturing short-term changes in cognitive capacity (i.e., fluid intelligence and working memory capacity) is not included in this preliminary *PastoralScape* model (see 38 for details of empirical data following the 2016–2017 drought in Samburu), future work will do so. The flexibility of the proposed human decision making sub-model motivates its introduction to ABMs in this paper.

The *PastoralScape* model is depicted in **Figure 1**. The sub-components of the current model are titled in blue. The solid connecting lines reflect the direction of interaction between model sub-components captured in *PastoralScape*. Three sub-models are numbered (1, 3). Foraging Condition is calculated

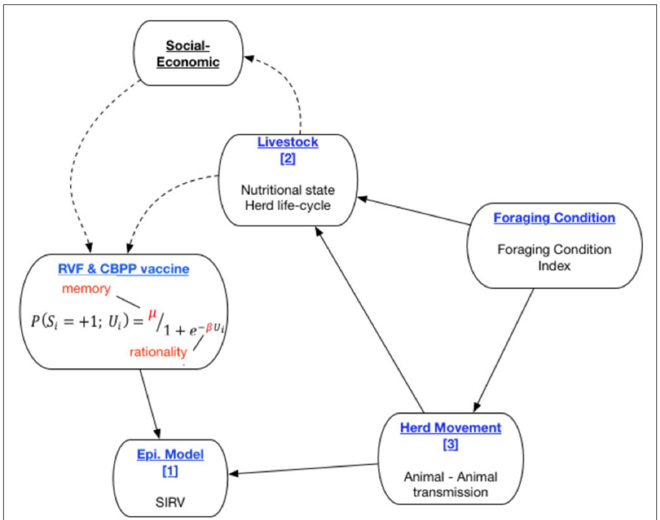

FIGURE 1 | Overview of preliminary PastoralScape sub-models.

independently of *PastoralScape*. The decision to vaccine livestock against RVF and CBPP is determined by the cognitive parameters μ (memory) and β (rationality). The dotted lines depict proposed extensions to the *PastoralScape* model connecting livestock and household socio-economic variables to dynamic changes to μ and β (Choi and Iles, under review; Iles et al., under review). The rest of the paper focuses on sub-components and the solid line relationships. A more detailed explanation of the interaction between sub-models is given when explaining the respective sub-models.

Adaptation and Learning

Head-of-household decision-making is modeled as a nested process and one that follows an existing specification (37). Decision-making is based on an Ising model, which incorporates individual willingness to act (f_i), public information (F), and network pressure (J_{ij}), to determine decision to sell (S: +1, −1) cattle.

$$U_i(t) = f_i + F(t) + \sum\nolimits_{j\epsilon\Upsilon_i} J_{ij} S_j (t-1), \qquad (1)$$

where U_i is perceived incentive to act, Υ_i is the neighborhood of agent i, and t is time (37). Agents act (+1, −1) when U_i is greater than some unobserved threshold. Ising models are frequently used in economics to model the effect of network pressure on decision-making (38–40). In this paper, we assume for simplicity that U_i is identical for every head-of-household and fixed through time. Individual willingness to act (f_i), public information [F(t)], and network pressure (J_{ij}) play no role in influencing the results of this paper. The values of these parameters are fixed across all runs and do not affect results.

By incorporating the Ising specification from equation 1 into a logit structure (see equation 2), the parameters of μ and β are created to *tune* resulting probabilities of a binary choice. The parameter μ ranges between zero and one and captures the degree of memory of the immediate past decision. For a head-of-household in the model, a degree of memory (μ) equal to one would imply that they remember exactly if and when they last administered an RVF or CBPP vaccine. A degree of memory equal to zero would imply that decision makers have no memory of the immediate past decision. In this scenario each decision is independent of the previous. The β parameter controls the amount of irrationality in the decision process ($Type\ 2: \beta \rightarrow \infty$ deterministic, and $Type\ 1: \beta \rightarrow 0$ random process). The degree of determinism used by the human agent is referred to as 'rationality'. This language follows that used by Bouchaud (37).

$$P(S_i = +1; U_i) = \frac{\mu}{1 + e^{-\beta U_i}}. \quad (2)$$

In the current preliminary model, the cognition parameters are held constant across the population of heads-of-households. That is, in this paper, we do not model heterogeneity of cognition parameters among the different heads-of-households. We assume homogenous parameters across all heads-of-households. However, this may not always be the case. Heterogeneity in the setting of μ and β is possible in future applications of the model. As individuals' perception of their current and future financial status differ by income and livestock loss (in the case of pastoralists), heterogeneous and dynamic cognition parameters could be incorporated in the future (Choi and Iles, under review; Iles et al., under review).

FIGURE 2 | Simulated world reflecting the natural environment of Samburu county.

Details

Input Data

The simulated "world" uses environmental data from south-western Samburu county, Kenya, from 2004 to 2015 (**Figure 2**). The "world" is constructed as a rectangular grid (35 × 55 km), which comprises 1 by 1 km sized cells. Village locations are fixed and align with the actual locations of surveyed villages (**Figure 3**). Agents reside either permanently (villages and heads-of-households) or temporarily (herdsmen and herds) within a given cell. When located within a cell agents have access to all resources co-located in the cell (i.e., other human agents and forage). It is assumed that when more than one herd and herdsman are co-located on a given cell they interact. Overlaying this rectangular "world" is a fixed social network of relationships between heads-of-households. All heads-of-households are linked to each other. For the purposes of this preliminary *PastoralScape* model, the importance of relationship weighting is equal across the social network. Due to this assumed social network weighting, the extent of the social network (either global or village based) has marginal effect on vaccination decisions.

The time period (2004–2015) coincided with three distinct droughts. The 2010–2011 and 2015–2016 droughts affected much of East Africa (3). A more localized drought in 2005–2006 affected Kenya (41). **Figure 2** locates the 35 km by 55 km area from which NDVI, FCI and precipitation data are drawn. This area of Samburu county is classified as semi-arid. The Samburu pastoralists are traditionally semi-nomadic, moving their cattle in dry seasons or drought to find better forage (42). The NDVI and precipitation data is from Google Developers (43, 44). Aggregate FCI data is used from the PLEWS model (45). The FCI data is scaled by the 1 km by 1 km grid NDVI values. FCI is used to reflect available livestock forage as it is believed to provide a more accurate measure than NDVI.

Household survey data from residents of five villages depicted in **Figure 3** inform the selection of average herd size per household. This survey also contains repeated measures of short-term cognition. Three rounds of data were collected from each village between October 2017 and September 2018 (46). This period coincided with the end of the 2015–2016 drought that gripped much of East Africa.

Submodels

A disease transmission sub-model [see sub-model (1) in **Figure 1**] uses a basic Susceptible, Infected, Recovered, Vaccinated (SIRV) structure. RVF and CBPP each have a separate SIRV sub-model. The transmission probabilities estimated in two papers are used to inform the selection of sub-model parameters (47, 48). **Figure 4** outlines the structure of the disease sub-model, while **Table 1** details the transition probabilities used for each disease. The use of Markov disease transmission models is common in ABMs (21). The V to S transition corresponding to a vaccine wearing off is modeled based on the time-since-vaccination transition probability dependent on the time spent in the vaccinated state. A herds' disease susceptibility is dependent on a collocated animal having the disease. The mixing of cattle affects herds' susceptibility (transition from S to I). All cattle within a village are located on the same cell. Once herds move away from their home village their susceptibility is dependent on collocating on a cell with

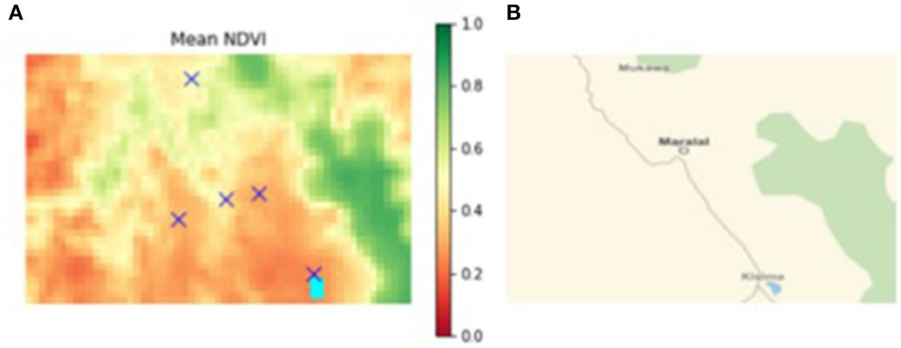

FIGURE 3 | (A) Mean NDVI of south-western Samburu county (location of sample villages denoted by "X"), **(B)** major road network connecting sample villages Kisima (south) to Poro (north), through Maralal.

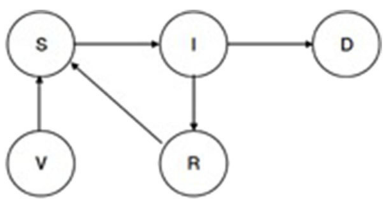

FIGURE 4 | SIRV epidemiological transmission model.

TABLE 1 | Markov transition probabilities.

	RVF	CBPP
Prob_si	0.14	0.024
Prob_ir	0.0001	0.0045
Prob_id	0.3	0.009
Prob_rs	0.0	0.0
Prob_vs	0.0	0.00091

s, susceptible; i, infected; r, recovered; d, death; v, vaccinated.

other herds. Therefore, herds' location, relative to other herds, within the grid space affect the likelihood of disease transmission. This results in the S to I transition to turn on and off, subject to the collocation of herds. Livestock susceptibility to RVF and CBPP does not account for the age or health profile of animals.

In addition to the risk of dying from RVF or CBPP, cattle may also die of old age or starvation. The non-disease related health of cattle is a separate sub-model [see sub-model (2) in **Figure 1**]. Non-disease health is measured along a zero to one continuum with zero representing death and one perfect health. Livestock require 0.1 units of feed per day. Available forage is calculated as the ratio of current available FCI relative to the historical average for the same place. When the ratio is one or greater, cattle are guaranteed to have food requirements met. For values less than one, cattle receive less than their required food, and thus livestock health degrades by 0.0175 per week. Symmetrically, if cattle receive more than their required food, their health improves by 0.0175 per week. Changes in livestock nutritional in-take is assumed uniform across a single herd. The age, gender, and health of cattle effects fertility. The occurrence of droughts during the timespan of the model serves two purposes. First, they help to diversify the causes of livestock death in the model to provide a sharper contrast with disease related deaths. Second, future versions of *PastoralScape* will use the experience of droughts to act as a stress on cognitive capacity. The experience of such stress will provide a heterogeneous cognitive shock to heads-of-households.

Herd movement [see sub-model (3) in **Figure 1**] is determined by herdsmen who have a 20-km radius of knowledge about surrounding foraging condition and long-term water availability. Herdsmen decide to move their cattle to a neighboring cell when the foraging condition of their village cell falls below the long-term average. Herdsmen continue to move as long as neighboring cells have higher FCI measures. After which time they return to their home village. The immediate effect of herds moving away from their home village is improved nutritional health. However, depending on the severity of a drought, herd movement within the grid-space may not continue to protect a herds' health. Each head of household manages 10 herdsmen, and each herdsmen has a herd of 20 cattle. Thus, each head of household is assumed to own 200 cattle. We simulate ten heads-of-households, for a total of 2,000 head of cattle simulated. The assumption that herdsmen have knowledge of surrounding foraging conditions is also reflected in the independent HerderLand ABM developed by Kennedy et al. (49). In the *PastoralScape* model the transition probability of moving from Susceptible to Infected is effective only when herds are collocated on the same cell. It is assumed that disease mixes completely through a single herd if one of the animals contracts the disease.

RESULTS

The livestock health sub-model captures the expected effects of the 2006, 2010–2011, and 2015 droughts on livestock health. **Figure 5** plots the weekly aggregate measure of livestock health between 2004 and 2015. Two large drops in livestock health are observed in 2010 (approximately week 310) and 2012

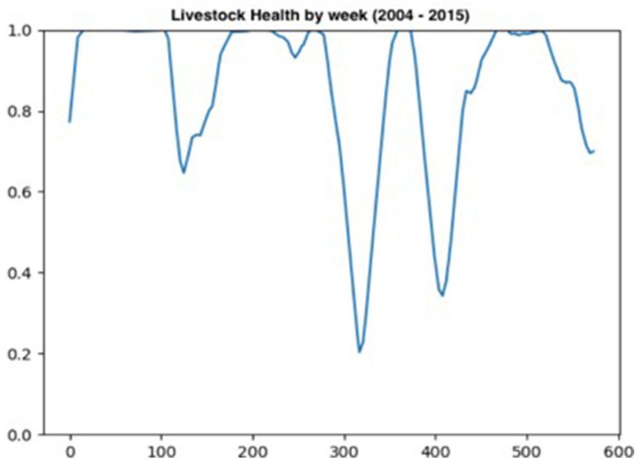

FIGURE 5 | Changes in Livestock health per week over 11.5 years.

TABLE 2 | Causes of livestock death resulting under different assumed values for parameter beta (rationality).

beta	Old age	Cause of Livestock Death Starvation	RVF	Sum RVF + CBPP	CBPP	Total
nill	1,428	9	635	1017	382	2,454
0.0	1,703	16	513	744	231	2,463
0.1	1,737	16	501	692	191	2,445
0.2	1,784	16	493	628	135	2,428
0.5	1,818	17	480	581	101	2,416
1.0	1,824	17	481	581	100	2,422
2.5	1,825	17	480	579	99	2,422
5.0	1,824	17	480	579	99	2,421

(approximately week 410). Smaller declines in livestock health are recorded in 2006 (approximately week 110) and in 2015 (approximately week 0).

The effect of synthetic uniform changes (across separate simulation runs, not through time within a given run) in the assumed rationality (β parameter) of heads-of-households on livestock deaths due to RVF and CBPP are recorded in **Table 2**. Deaths due to the combined effects of RVF and CBPP diminish in absolute and relative terms as β (rationality) increases. As β increases from 0.0 (random) to 0.5 (more rational) the combined total of livestock disease deaths decreases from 744 to 581 out of ∼2,430 head of cattle that die during the simulation. Results also remind us, though, that a trade-off exists between deaths by disease and old age. An increase in rationality reduces deaths due to disease, but also increases deaths due to old age.

Across a select range of μ (memory) and β (rationality) parameter combinations, a stable number of cattle is achieved. This stable level is achieved by altering the memory and rationality parameters, which results in changes to the number of livestock vaccinated for RVF and CBPP. **Figure 6** presents the number of live cattle averaged over 50 simulation runs for each combination of μ and β. Each row of the matrix represents results for μ values 0.7, 0.8, 0.9, and 1. Each column represents results for β values 0, 0.5, and 1. The decline in the number of live cattle in the model declines over time. However, the rate of decline is more gradual as μ (memory) and β (rationality) parameter values increase. In **Figures 6E,F,H,I,K,L** the rate of decline appears most gradual. The parameter combinations of these sub-plots are β is $\geq$0.5 and μ is $\geq$0.8.

Figure 7 presents the number of RVF and CBPP vaccination doses given across all cattle owned by the heads-of-households assume various combinations of μ and β parameter values. Two distinct patterns are observed. First, across low levels of μ (memory) the number of CBPP vaccinations outnumber those for RVF for individual heads-of-households. This hints at a potential difference in the role of memory for vaccination decisions related to RVF (a cyclical, more predictable disease requiring once-a-lifetime vaccine) vs. CBPP (a less predictable disease requiring booster vaccines). In **Figures 7B,C** (where $\beta = 0.5$ and $\mu = 0.7$, and $\beta = 1.0$ and $\mu = 0.7$) the number of vaccination decisions for both RVF and CBPP declines over time. Second, the sum of the number of RVF and CBPP vaccinations is similar across the majority of parameter combinations. At low levels of rationality (β), irrespective of the level of memory, the proportion of vaccination decisions is <50%. Only once β is $\geq$0.5 and μ is $\geq$0.8 does this proportion pass 50%. We discuss these two results in more detail below.

DISCUSSION

The sensitivity analysis of the μ and β parameters enable a comparison across decision maker typologies. The graphs **Figures 6C,J,H** in represent decision makers with different combination of μ (memory) and β (rationality). Across the range of μ and β values graphs **Figures 6C,J** have parameter combinations at opposite extremes. Graph **Figure 6H** represents moderate levels of memory ($\mu = 0.9$) and rationality ($\beta = 0.5$). This parameter combination may be not dissimilar to a person with "standard" levels of memory and rationality—strong but not perfect. At these strong, but not perfect, parameter values the number of cattle in the model is one of the most stable, after 350 weeks. The corresponding plot in **Figure 7H** (graph) has positive vaccine decisions for both CBPP and RVF at 80 percent or greater. The scenario with decision-makers with perfect memory of the past decision ($\mu = 1$), but low rationality ($\beta = 0$) the graph **Figure 6J** in has the number of cattle in the model rapidly declining after 350 weeks. The corresponding graph in **Figure 7J** (graph) has positive vaccine choices at ∼50 percent for both CBPP and RVF. For the opposite parameter mix of perfect rationality ($\beta = 1$) and relatively weak memory ($\mu = 0.7$), graph c in **Figure 6**, the decline in the number of cattle alive in the model appears to decrease at an equally rapid rate after 350 weeks. Under this parameter scenario, graph of **Figure 7F**, the number of vaccination decisions start at 60% and then progressively decline to ∼40%.

The lower efficacy of the CBPP vaccine, relative to the once-for-life RVF vaccine, and the need to decide annually whether to

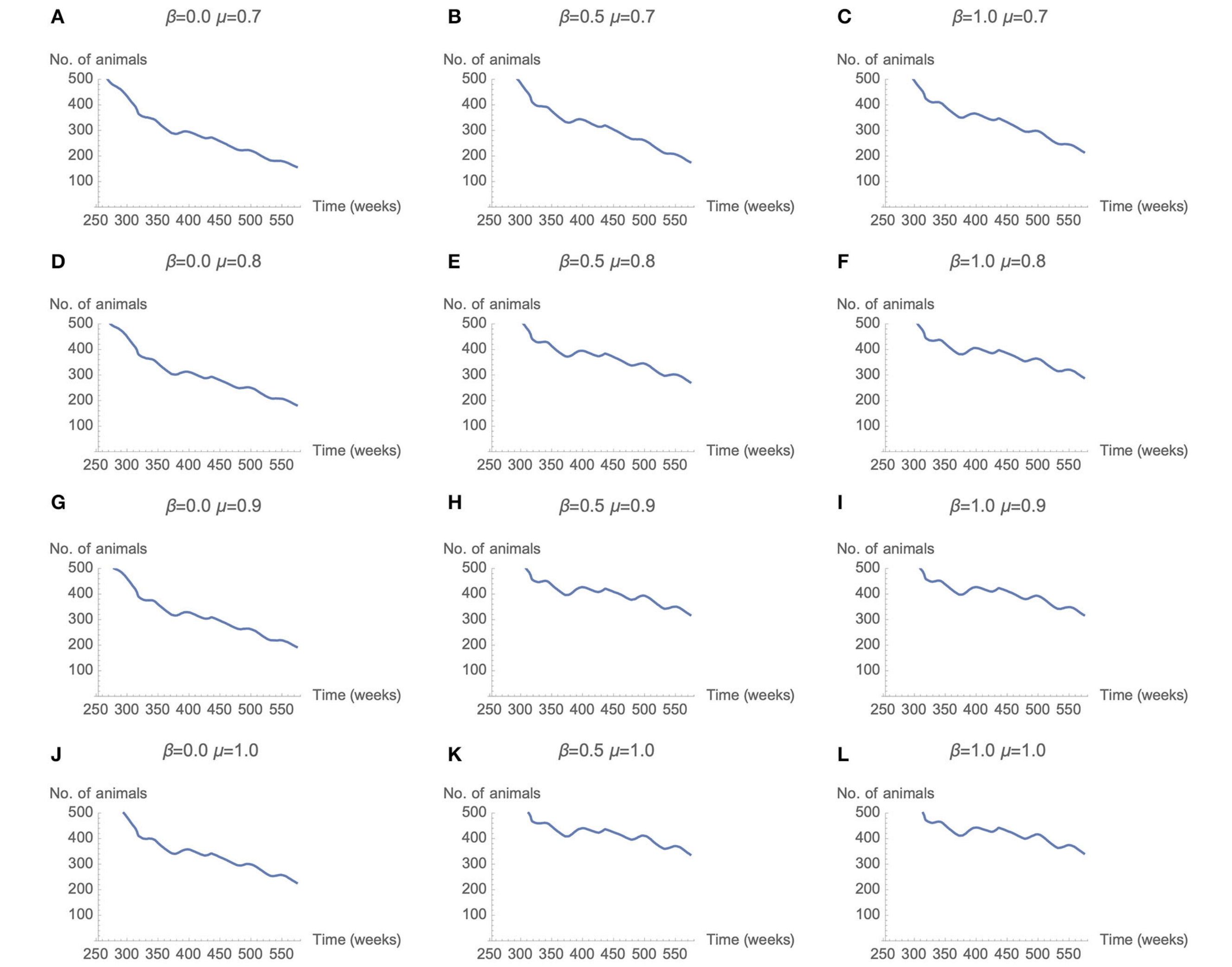

FIGURE 6 | Total herd population over time as μ and β parameters change (50 seeds used per parameter combination).

vaccinate cattle against CBPP increases the effect of changes in the μ and β parameters. Increasing β (rationality) values from 0.0 to 0.5 generated a 57 percent decrease in CBPP related cattle deaths, compared to a 6 percent decrease for RVF (**Table 2**). Increasing μ (memory) from 0.7 to 0.9 had a disproportionate positive effect on CBPP vaccine up-take compared to RVF (**Figure 7**). The relative lower effect of μ and β on RVF vaccine up-take is intuitive. While the risk of RVF is periodic (strongly associated with high rainfall and mosquito vectors), the life-time immunity given by the vaccine makes the need for heads-of-households to use "past experience" or memory of the most recent decision less important. Although the spread of both diseases are uncertain, RVF risk is periodically more certain following the onset of heavy rains generated by El Nino/Southern Oscillation weather pattern (30). If one believes that cattle will be exposed to high risk of RVF during the animal's life, then vaccinating early in the animal's life (whether or not the present risk of RVF is great) is sensible. The same cannot be applied to the annual booster for CBPP. The differences in uncertainty of disease risk for RVF and CBPP, as an explanation for the differing effects of μ and β, is further strengthened in light of the fact that no outbreaks of RVF or CBPP have recently been recorded in Samburu.

The *PastoralScape* ABM provides a realistic simulation of the environmental conditions of south-western Samburu by integrating historical measurements of the environment to drive mathematical models. This modeling realism of the natural environment provides a foundation to model livestock nutritional health, and herd mixing though common grazing of cattle within villages and herd movements. While the ABM presented captures "high-level" environmental change, it does so in a manner that motivates secondary dynamics of cattle health. Declines in available forage in and around villages prompts herdsmen to move cattle to protect against further livestock health declines. While model tuning and extended design is required to better capture the interactions between livestock

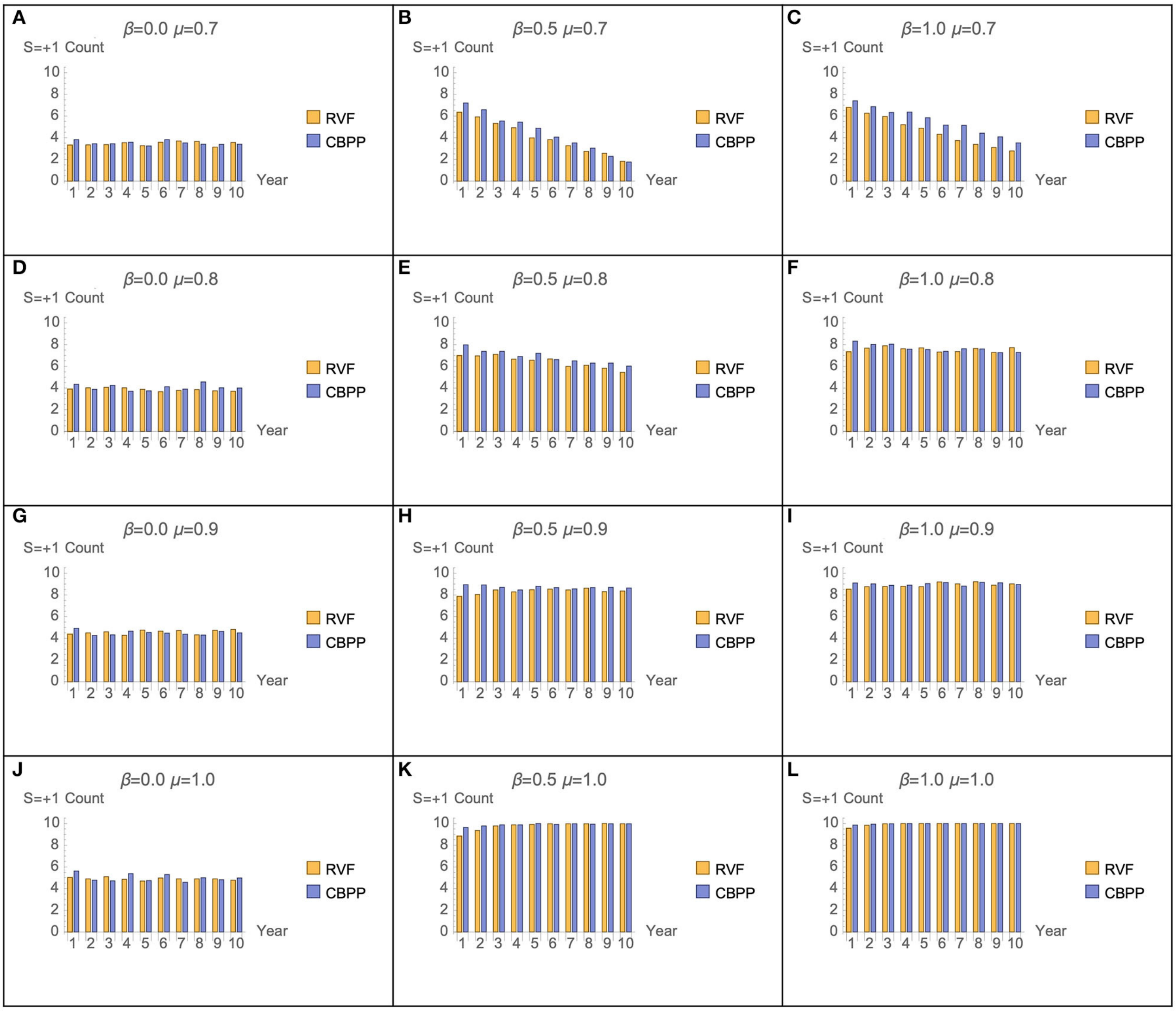

FIGURE 7 | Ratio of RVF and CBPP vaccination decisions for β and μ parameter combinations (50 seeds used per parameter combination).

non-disease health, herd movement and herd management, the current *PastoralScape* model provides a sound basis to identify the utility of using a RFIM to represent individual decision-making dynamics.

The *PastoralScape* model offers a platform to better understanding the relationship between natural systems and human decision making. Disease transmission is one such natural system. The results of the preliminary *PastoralScape* ABM highlight the effect of two different cognitive measures on vaccines with contrasting booster requirements. The effect of altering only β (rationality) or both μ (memory) and β (rationality) on the susceptibility of cattle to RVF and CBPP is meaningful. Modeling the effect of dynamic cognitive capacity, whether uniform or non-uniform across a population, on a range of decision contexts is supported by detailed experimental and non-experimental findings [(Choi and Iles, under review); (36)]. The incorporation of an RFIM for decision making within an ABM, as demonstrated by the *PastoralScape* model, provides a clear avenue to extend livestock disease modeling (6). Extending the *PastoralScape* model to include household income will allow for simulations of the effect of droughts on pastoralists' decision-making, including preventative livestock health measures.

The use of the RFIM, as specified by Bouchaud (37), in the current preliminary *PastoralScape* ABM provides a viable response to the need to more realistically model the temporal dynamics of binary decision making. By considering the short-run dynamics of changes in memory and rationality, dynamic decision making may be incorporated into ABMs. While such short-run changes are not currently implemented, the authors plan to do so in future work. The constructs of working memory capacity and fluid intelligence are measures that relate to β (fluid intelligence) and μ (working memory capacity). Working memory capacity measures the ability to recall salient information in the face of distractions (32, 50). Fluid intelligence measures one's ability to apply abstract reasoning (51). Dynamic changes in cognitive capacity due to stress is in keeping with the Mullainathan and Shafir's "scarcity thesis" (9).

Analyzing only μ and β (as two out of five RFIM parameters) for their effect on the probability of vaccine up-take and cattle mortality is deemed most manageable for such a preliminary model. In addition, the assumption of homogeneity of parameter levels aids the communication of the preliminary *PastoralScape* model. Consideration of the effects of the other three parameters (willingness to act, public information, and social network pressure) on livestock vaccine decision making is planned. The rapidly increasing combination of parameter combinations makes this difficult (26 combinations of five continuous parameters). The parameter μ (memory) and β (rationality) were selected first due to their relevance to the literature concerning individuals' internal barriers to experiencing poverty alleviation. The scarcity and aspiration failure these are two prominent examples (10, 52). Analysis of the effects of fluid intelligence (proxy for rationality) and working memory capacity (proxy for memory) among the Samburu shows that households in the lowest income quartile (ultra-poor households) have distinct effect on the likelihood of tick treatment and CBPP vaccine choice (Choi and Iles, under review).

The present research describes preliminary work in developing a fully coupled natural and human simulation that models livestock vaccine choice, herd management, and resulting causes of death. In addition, the model presented here provides a feasible alternate to the more common but limited assumption of a fully rational agent.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

RI devised the project and the main conceptual ideas. MS worked out the technical details and wrote the code. OA provided the GIS data, while EL and CM verified the epidemiological and animal health submodels. RI drafted the manuscript with assistance from MS. OA, EL, and CM provided comments on the final draft. All authors contributed to the article and approved the submitted version.

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Economic Analysis of Increasing Foot-and-Mouth Disease Vaccination Frequency: The Case of the Biannual Mass Vaccination Strategy

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Biannual mass vaccination is a routinely applied foot-and-mouth disease (FMD) control strategy in Turkey. However, because biannual mass vaccination may leave significant immunity gaps, this strategy may cause economic losses because of possible FMD infections. In high-risk areas—such as border cities, it was suggested by the government to increase the vaccination intervals in order to decrease the FMD infection risk. This study analyses and compares the economic effects of a biannual mass vaccination regime and vaccination every 4 months as an alternative strategy in border cities by using partial budgeting approach. Biannual mass vaccination was used as a baseline scenario. Data on the impact of FMD on animal health and production parameters for 2018 were obtained from the OIE-WAHIS system and complemented by literature data and expert opinion. In the partial budgeting model, weight loss was considered as a major loss of income because majority of the farming systems are based on cattle fattening in the border cities of Turkey. Results revealed that the net economic impact, which is the benefit that exceeds the losses and costs of increasing the frequency of vaccination, is 76.4 TL ($15.9) per cattle. The sensitivity analysis showed that average body weight and weight losses when infected had more effect on net impact changes than market prices. The lower and upper FMD incidence variability resulted in 19.2 TL ($4) and 190.8 TL ($39.6) of net impact per cattle, respectively. The new FMD control strategy would make a total net economic impact of 5,274,836 TL ($1,094,250) for a population of 800,970 fattening cattle in border cities. The results of this study indicated that intense FMD control strategies may be more cost effective than the current control strategies, especially in high-risk areas. Future studies with more comprehensive epidemiological and economic data must be conducted to analyze and compare alternative FMD control strategies in Turkey.

Keywords: FMD (Foot and Mouth Disease), vaccine, partial budgeting, Turkey, cattle

INTRODUCTION

Foot-and-mouth disease (FMD) imposes substantial production losses to farmers by causing decrease in milk and meat yield, fertility disorders, and mortality for young stock in cloven-hoofed animals (including cattle, pig, sheep, goat, and deer). It directly affects the production of animal origin food and eventually affects the product prices at a national scale in case of a large outbreak (1). Studies reported that the disease cause an 80% reduction in milk yield in its chronic form (2, 3), 2–5% of death among young stock (4), 25% decrease in live weight, and 10% increase in abortion rate (5), which, in total, results in 7–12% decrease in income of a farmer (6).

Turkey is an FMD endemic country where the disease has been eradicated from the Thrace region but is still present in the Anatolian part of the country (**Figure 1**). The prevalence of the disease has been reduced from 45 to 5% between 2008 and year 2018 as a result of the government's control policies (7). The Turkish government aims to achieve an OIE status of FMD free with vaccination by 2023 by improving clinical surveillance programs in provinces along the border, vaccine effectiveness, and management of animal movement (8). Indeed, enhancing border security is a paramount strategy since a great number of studies demonstrated the role of legal and illegal animal movement in spreading FMD (9, 10). When comparing the border regions of Turkey with the West of Anatolia, a significant difference is observed in the number of outbreaks (11). This could be due to having FMD endemic neighbors, large-scale illegal cross-border movement, and insufficient biosecurity. In high-risk areas, there is an increasing need to sustain a high level of vaccine efficacy and protection in order to ensure FMD control throughout the country. Therefore, in regions where the outbreak incidence is high, it is recommended to increase the vaccination intervals by the government.

Cattle breeding in border cities of Turkey is conducted by smallholders and farmers raising local breeds, indigenous breeds, and their crosses for milk and meat production. Cross breeds of Holsteins, Simmental, and Brown Swiss are the most favored breeds in these areas. Male calves that are born on dairy farms are taken at the age of 4–8 months and at about 120–200 kg of live weight for fattening purposes and mostly for the Kurban festival of slaughter. These animals are then sold at a weight of 300–600 kg depending on the breed after they become 2 years old. Calves receive their first FMD vaccine (containing six PD50) doses at the age of 2 months. Vaccination is applied biannually as the current strategy of the government to control and reduce FMD outbreaks.

The time since the last vaccination have an effect on expected immunity. With biannual mass vaccination, sustained immunity level cannot be achieved due to rapidly declining antibody titres, which require multiple doses of vaccination (12). A high-potency vaccine or a vaccination scheme with increased frequency of administration is required in order to sustain immunity level. However, engaging farmers in disease control strategies is quite challenging, as smallholders' willingness to participate in a disease control program is reported to be low if the vaccination is not free of charge (13). Economic impact assessment studies of disease control policies using analytical approaches such as partial budgeting would encourage farmers to participate in the disease control program by demonstrating the obtained benefit from alternative policies. Furthermore, economic impact assessment studies support the veterinary authorities with decision support information to justify and adjust control plans if necessary.

Partial budgeting is an analytical economic method that can be used for comparing alternative disease control measures on a farm. It is used to estimate possible changes that are caused by a proposed disease control plan by considering benefits and costs that are available (14). To our knowledge in Turkey, FMD control measures have not been compared by using any economic modeling techniques before. In other FMD endemic settings, studies using partial budgeting approach determined a positive net return considering the application of mass vaccination campaigns (15, 16).

In this study, we aim to analyze and compare the net economic impact of increasing the vaccination frequency to 4 months in border districts of Turkey vs. the current biannual vaccination policy, using partial budget analysis. This analysis provides supportive information for the policy makers in order to protect smallholder income for a sustainable production and prevent losses, which are caused by FMD.

MATERIALS AND METHODS

Data

Primary epidemiological data was obtained through the OIE's 2018 country reports for each city in border districts. Financial information was obtained through the market values for the year 2018. Literature values and expert views were also included as secondary data. FMD incidences and mortality for each city in 2018 are given in **Appendix 1**. We hypothesized that increasing vaccination frequency would decrease the FMD incidence, mortality, and morbidity. Therefore, in order to reflect the effect of increasing vaccination frequency on FMD incidence, mortality, and morbidity, we multiplied the observed FMD incidences, mortality, and morbidity by the relative risk (RR) values considering the number of received doses of FMD vaccination, which was reported by Knight–Jones et al. (17).

The formulas for estimating the FMD incidence, mortality, and morbidity used in the scenario are presented below:

$$\mathrm{Inc}_{\mathrm{Sc}} : \mathrm{Inc}_{\mathrm{Bc}} * \mathrm{RR} \quad (1)$$

with $\mathrm{Inc}_{\mathrm{Sc}}$ being the FMD incidence rate for the cth city in the border district used in vaccination in the 4-months scenario. The $\mathrm{Inc}_{\mathrm{Sc}}$ value is calculated by multiplying the baseline FMD incidence for the c^{th} city with the relative risk value.

$$\mathrm{Mort}_{\mathrm{Sc}} : \mathrm{Mort}_{\mathrm{Bc}} * \mathrm{RR} \quad (2)$$

with $\mathrm{Mort}_{\mathrm{Sc}}$ being the FMD mortality rate for the cth city in the border district used in the scenario. The $\mathrm{Mort}_{\mathrm{Sc}}$ value is

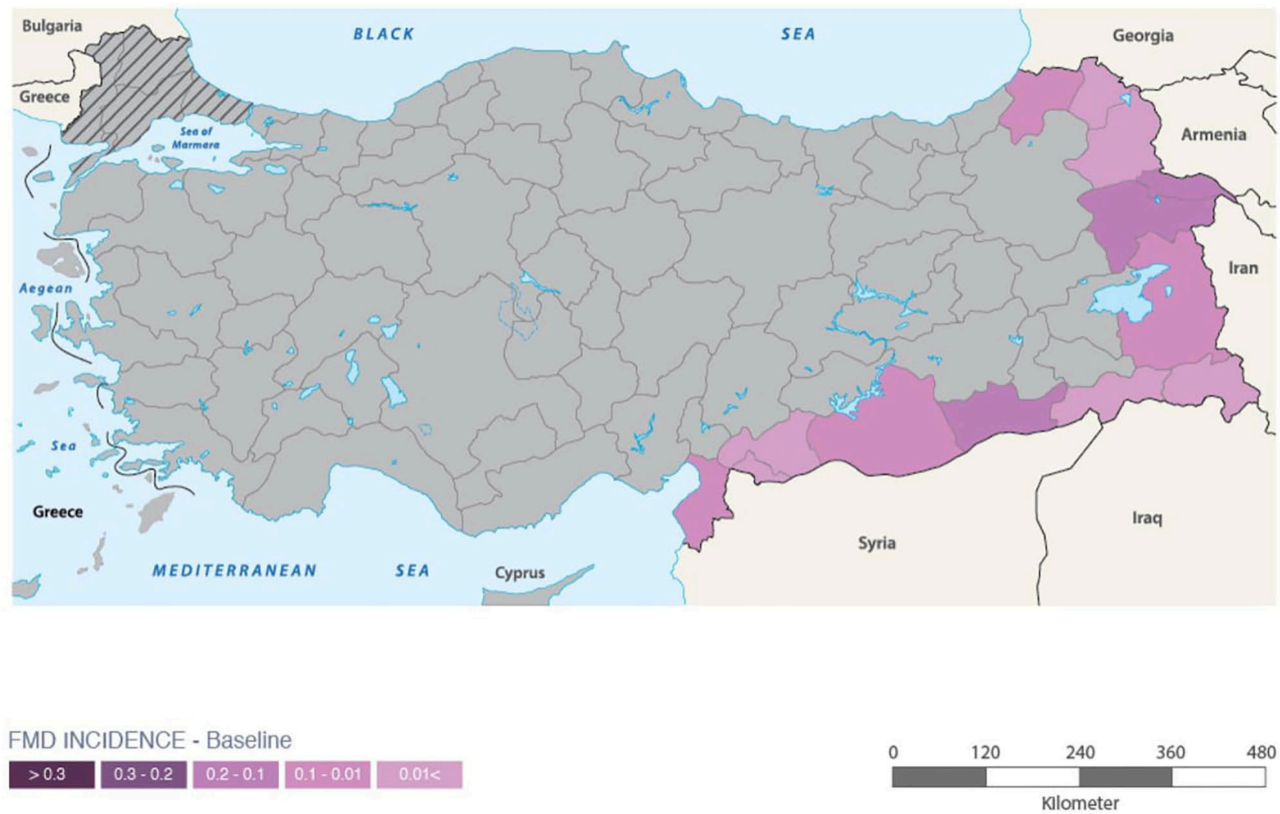

FIGURE 1 | Map of Turkey. FMD incidences in border regions were highlighted relatively. The hashed lines show the Thrace region which is FMD free where the gray part depicts Anatolia.

calculated by multiplying the baseline FMD mortality for the cth city with the relative risk value.

$$\mathrm{Morb_S : Morb_B * RR} \tag{3}$$

with $\mathrm{Morb_S}$ being the FMD morbidity rate for the district level used in the scenario. The $\mathrm{Morb_S}$ value is calculated by multiplying the baseline FMD morbidity level with the relative risk value.

Partial Budgeting Approach

In order to compare the impact of vaccination in a 4-month-interval strategy in border regions to the baseline scenario, we applied a deterministic economic model by using partial budget analysis. FMD incidence, morbidity rate, mortality rate, weight loss when infected, average body weight, average duration of illness, value of live weight, cost of replacement, cost of FMD treatment, cost of FMD vaccination, cost of feed, and cost of veterinary services were included as inputs. The input variables used in the partial budget analysis and sources are given in **Table 1**.

Weight loss was considered as the major production loss because in the eastern part of Turkey, fattening is an important production system when comparing border cities to other regions of the country. Therefore, other production parameters such as decrease in milk production or increase in abortion rate were not considered in the analysis.

In the partial budgeting model, we also included the potential immunity gap (IG), which would potentially be caused by a decrease in antibody levels after receiving an FMD vaccine dose. The antibody levels were reported to decline by 0.5% per day (17). We multiplied the reported daily antibody decrease for 6- and 4-months of vaccination intervals in order to find out immunity gaps for base ($\mathrm{IG_B}$) and scenario ($\mathrm{IG_S}$).

Our partial budget model consists of the components that are described below:

(1) Additional return (Ar): is primarily derived from the weight gain achieved by a healthy cattle, calculated as the average duration of illness multiplied by the estimated mean daily weight gain and the value of the live weight per kg. This value is then multiplied by the annual disease incidence, morbidity, and immunity gap.

$$\sum\nolimits_{Sc} Ar = [(\mathrm{ADG_{healthy}} * \mathrm{t}) - (\mathrm{ADG_{healthy}} * \mathrm{W_{loss}} * \mathrm{t})] * \mathrm{P_{LW}} * \mathrm{Inc_{Sc}} * \mathrm{Morb_S} * \mathrm{IG_S} \tag{4}$$

$$\sum\nolimits_{Bc} Ar = [(\mathrm{ADG_{healthy}} * \mathrm{t}) - (\mathrm{ADG_{healthy}} * \mathrm{W_{loss}} * \mathrm{t})] * \mathrm{P_{LW}} * \mathrm{Inc_{Bc}} * \mathrm{Morb_B} * \mathrm{IG_B} \tag{5}$$

TABLE 1 | Partial budget input variables and sources.

Inputs	Baseline Value	Scenario Value	Source
Foot-and-mouth disease (FMD) incidence[#], %	12.4 ± 0.1[a]	5.9 ± 0.1[a]	Calculation (7)
Morbidity rate[#], %	60.0 (42.2–72.3)[b]	30.0 (20.9–34.3)[b]	(18)
Mortality rate[#], %	1.4 ± 2.1[a]	0.6 ± 0.9[a]	Calculation (7)
Weight loss when infected, %	25 (15–30)[b]	25 (15–30)[b]	(5)
Average body weight, kg	355[c]	355[c]	(5)
Average duration of illness, d	13.3 ± 5.5[a]	13.3 ± 5.5[a]	Expert survey
Value of live weight, TL	15.3 ± 1.3[a]	15.3 ± 1.3[a]	(19)
Cost of replacement, TL	6,673.9 ± 1,266.2[a]	6,673.9 ± 1,266.2[a]	(19)
Cost of FMD treatment, TL	441.7 ± 210.8[a]	441.7 ± 210.8[a]	Expert survey
Cost of FMD vaccination, TL	9.6 (0.4–3)[b]	14.4 (0.4–3)[b]	(12)
Cost of feed, TL/day	11.8 ± 3.8[a]	11.8 ± 3.8[a]	(20)
Cost of veterinary services, TL/day	0.8[c]	0.8[c]	Calculation (21)

[#]When calculating the FMD incidence, morbidity, and mortality values for the scenario, the baseline incidence, morbidity, and mortality values were multiplied by the relative risk ratios. The relative risk ratio is the likelihood of an animal to become infected considering the received number of FMD vaccination doses (17).

TL, Turkish Lira (Turkish currency).

[a]Normal distribution: mean ± SD. [b]Normal distribution: mean (CI 95%). [c]Data available with mean only.

where $ADG_{healthy}$ represents the average daily weight gain of healthy cattle, t represents the average duration of the disease, P_{LW} stands for the value of live weight, and W_{loss} represents the percentage of weight loss when infected.

(2) Reduced cost (Rc): is primarily derived from the cost of disease treatment, cost of weight loss, and cost of replacement animals. The summation of these costs is multiplied by the disease incidence, morbidity, and immunity gap.

$$\sum{}_{Sc}Rc = [\text{Treat.cost} + \text{W}_{\text{loss}}.\text{cost} + (\text{Rep.cost} * \text{Mort}_{\text{Sc}})] * \text{Inc}_{\text{Sc}} * \text{Morb}_{\text{S}} * \text{IG}_{\text{S}} \quad (6)$$

$$\sum{}_{Bc}Rc = [\text{Treat.cost} + \text{W}_{\text{loss}}.\text{cost} + (\text{Rep.cost} * \text{Mort}_{\text{Bc}})] * \text{Inc}_{\text{Bc}} * \text{Morb}_{\text{B}} * \text{IG}_{\text{B}} \quad (7)$$

$$\text{W}_{\text{loss}}.\text{cost} = \text{W}_{\text{loss}} * \text{Av}_{\text{LW}} * \text{P}_{\text{LW}} \quad (8)$$

where Treat.cost represents the FMD treatment cost per infected cattle, W_{loss}.cost is the cost of weight loss, and Rep.cost stands for the replacement cost in case of a death caused by FMD. Cost of weight loss is calculated by multiplying the average percentage of weight loss by the average body weight at the time of infection and price of live weight. Av_{LW} represents the average live weight of cattle at the time of infection.

(3) Return forgone (Rf), was considered to be zero because selling dead animals is not practiced in Turkey.

(4) Additional costs (Ac): These are of the alternative plan, referencing the purchase and administration of the FMD vaccine. Furthermore, due to lower mortality rates, additional feed and veterinary cost are included as extra costs.

$$\sum{}_{Sc}Ac = (\text{Vac.cost} * 3) + \text{Add.feed.cost} + \text{Add.vet.cost} \quad (9)$$

$$\sum{}_{Sc}Add.feed.cost = \text{Feed.cost} * \text{Inc}_{\text{Sc}} * \text{Morb}_{\text{S}} * \text{Mort}_{\text{Sc}} * \text{IG}_{\text{S}} \quad (10)$$

$$\sum{}_{Sc}Add.vet.cost = \text{Vet.cost} * \text{Inc}_{\text{Sc}} * \text{Morb}_{\text{S}} * \text{Mort}_{\text{Sc}} * \text{IG}_{\text{S}} \quad (11)$$

$$\sum{}_{Bc}Ac = (\text{Vac.cost} * 2) + \text{Add.feed.cost} + \text{Add.vet.cost} \quad (12)$$

$$\sum{}_{Bc}Add.feed.cost = \text{Feed.cost} * \text{Inc}_{\text{Bc}} * \text{Morb}_{\text{B}} * \text{Mort}_{\text{Bc}} * \text{IG}_{\text{B}} \quad (13)$$

$$\sum{}_{Bc}Add.vet.cost = \text{Vet.cost} * \text{Inc}_{\text{Bc}} * \text{Morb}_{\text{B}} * \text{Mort}_{\text{Bc}} * \text{IG}_{\text{B}} \quad (14)$$

where Vac.cost represents the FMD vaccination cost, Add.feed.cost stands for the additional feed cost due to lower mortality that will be needed for a cattle per year, and Add.vet.cost is the additional veterinary costs that caused a lower mortality that will be needed in treating healthier animals per year.

Sensitivity Analysis

Due to the fluctuation of prices and disease parameters, we applied sensitivity analysis by considering the minimum, most likely, and maximum values of cattle price, value of live weight, FMD treatment cost, percentage of weight loss when infected, duration of disease, and average body weight at the time of infection. Furthermore, in order to understand how the lower and upper disease incidences affects the net impact of vaccination in 4 months, 50% of the lower and upper values of the observed FMD incidences were included in the sensitivity analysis.

RESULTS

The results of the partial budget analysis revealed that the net impact of increasing vaccination frequency by up to three times per year in high-risk areas would be 76.4 TL/cow. When the minimum and maximum values of the disease and economic parameters were included in the sensitivity analysis, the average body weight at the time of infection and weight loss when infected were found to be the most influencing parameters that affect the outcome of the partial budget model (**Figure 2**). When the minimum value for the percentage of weight loss was considered, the result of the partial budget analysis was 38.7 TL/cow, which was the lowest result. Furthermore, the maximum value of the average body weight at the time of infection resulted in the highest net impact of the overall partial budget analysis (127.7 TL/cow). In this study, the results of the sensitivity analysis showed a positive net impact for all included parameters, even for the most influencing parameters, and changing economic parameters did not affect the net impact of increasing the vaccination interval strategy (**Table 2**).

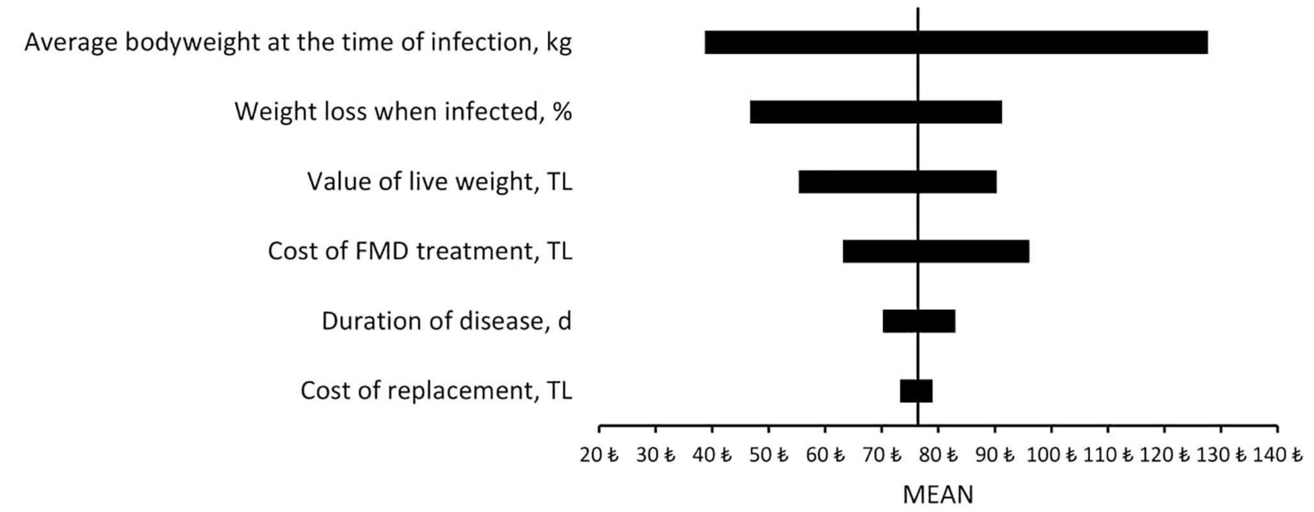

FIGURE 2 | Sensitivity analysis results of FMD vaccination strategy.

TABLE 2 | Changes in partial budget analysis results by applying the minimum, most likely, and maximum input values.

Variable	Value	Net impact of PB (TL)	Net impact of PB ($)	Change from baseline (TL)	Change from baseline ($)
Cost of replacement, TL	6,673.9	76.4			
Minimum	4,003.7	73.2	15.2	3.2	0.7
Maximum	8,866.2	79.0	16.4	2.6	0.5
Value of live weight, TL	15.3	76.4			
Minimum	11.6	55.3	11.5	21.1	4.4
Maximum	17.7	90.4	18.7	13.9	2.9
Duration of disease, days	13.3	76.4			
Minimum	7	70.2	14.6	6.2	1.3
Maximum	20	83.0	17.2	6.6	1.4
Average body weight, kg	355	76.4			
Minimum	175	38.7	8.0	37.7	7.8
Maximum	600	127.7	26.5	51.3	10.6
Weight loss when infected, %	25	76.4			
Minimum	15	46.7	9.7	29.7	6.2
Maximum	30	91.3	18.9	14.9	3.1
Cost of FMD treatment, TL	441.7	76.4			
Minimum	200	63.1	13.1	13.2	2.8
Maximum	800	96.1	19.9	19.7	4.1

TL, Turkish Lira (Turkish currency).

TABLE 3 | Results of sensitivity analysis on FMD annual incidence while comparing baseline and partial budget (PB) results.

Variable	Mean value	Net impact of PB (TL)	Net impact of PB ($)
FMD incidence (baseline)	0.12	76.4	15.9
Lower incidence estimation	0.06	19.2	4.0
Upper incidence estimation	0.24	190.8	39.6

TL, Turkish Lira (Turkish currency).

Varying the FMD incidence by 50% lower and upper values showed a positive net impact (**Table 3**). In one case of increasing the FMD incidence by 50%, the sensitivity analysis results were 190.8 TL/cow and 19.2 TL/cow when the incidence rate was lowered by 50%. This result implies that even with a low risk of FMD, increasing the vaccination interval was still profitable.

In **Table 4**, gain, losses, and net impact of the partial budget analysis were shown for each city in the bordering region. The total net impact was found to be 5,274,836 TL. Two cities located in the East Anatolia Region, Agri (3,026,633.6 TL) and Igdir (851,181.2 TL), were determined as the cities with the highest net impact. However, also in the same region, Van (1,684.5 TL) was the city with the lowest net impact.

DISCUSSION

In this study, a deterministic approach was used to determine whether the proposed vaccination strategy is profitable for the farmers. The partial budget analysis showed that increasing the vaccination frequency produced a positive net impact of 76.4 TL/cow, indicating that FMD causes severe losses to farmers. In the analysis, the economic consequences of weight loss due to foot-and-mouth disease were the only effect that was considered, as the majority of farms in Eastern Turkey are for fattening. In a study conducted by Truong et al. (16), it

TABLE 4 | Gain (reduced costs and additional revenue), loss (extra cost and revenue forgone), and net impact from partial budget analysis of vaccination in the 4-months strategy compared with the baseline per each border city in 2018.

City	Gain (TL)	Gain ($)	Cost (TL)	Cost ($)	Net impact (TL)	Net impact ($)	Cost/Benefit
Agri	3,104,790.8	644,080.7	78,157.3	16,213.5	3,026,633.6	627,867.1	0.03
Ardahan	141,358.7	29,324.5	12,848.0	2,665.3	128,510.7	26,659.2	0.09
Artvin	1,015,849.6	210,735.3	305,117.9	63,295.9	710,731.7	147,439.4	0.30
Gaziantep	157,763.7	32,727.7	155,975.0	32,356.6	1,788.7	371.1	0.99
Hatay	424,401.9	88,041.1	292,581.2	60,695.2	131,820.6	27,345.8	0.69
Igdir	876,803.4	181,890.5	25,622.2	5,315.3	851,181.2	176,575.3	0.03
Kars	160,154.6	33,223.6	17,562.8	3,643.4	142,591.8	29,580.3	0.11
Mardin	511,387.5	106,086.0	494,366.0	102,554.9	17,021.5	3,531.1	0.97
Sanliurfa	286,488.6	59,431.3	23,616.8	4,899.3	262,871.8	54,532.1	0.08
Van	3,341.27	693.1	1,656.8	343.7	1,684.5	349.5	0.50
TOTAL	6,682,340.0	1,386,233.8	1,407,503.9	291,983.0	5,274,836.1	1,094,250.8	0.36

TL, Turkish Lira (Turkish currency).

was found that dairy farmers would get a higher benefit than beef farms by applying biannual FMD vaccination. Therefore, the net impact of partial budget analysis would possibly be higher if the effect of milk reduction and fertility disorder had been included.

A sensitivity analysis was performed using both disease and economic parameters including cattle value, value of live weight, duration of disease, average body weight at the time of infection, percentage of weight loss when infected, and cost of treatment. The net benefit of increasing vaccination interval under uncertainty remained at 38.7 TL/cow or higher.

Vaccination is an important strategy in controlling FMD. Although in Turkey preventive vaccination campaign is applied biannually in Anatolia and three times a year in the Thrace (FMD free) region, full protection cannot be achieved. If a booster dose is not applied during the vaccination campaigns, there can be an immunity gap within 6 months (12), which requires several doses of vaccine. This study supports the introduction of a new vaccination interval scheme.

The overall net impact of the proposed vaccination scenario in border regions shows that some cities are more likely to gain a higher net impact, possibly due to their higher FMD incidence rate. The outcome reveals that an effective disease control strategy will be economically beneficial especially in high-risk areas. For countries with a limited export opportunity, controlling diseases is recommended to target high-risk areas to generate a positive economic return (4). It was estimated that the net benefit of the proposed vaccination scenario for the city Agri is 1.7% of its gross domestic product from agriculture (22).

Most farms are smallholding in border cities in Turkey, and they are dependent on livestock. Although extensive farmers are less motivated to participate in FMD control programs (23), the farmers' willingness to pay for vaccines and their participation in vaccination campaigns are reported to be increased through awareness of vaccine benefits (24). In Turkey, FMD vaccination is given without any charge; farmers only pay for the vaccine application cost to the state veterinarian. However, besides the cost of vaccine, the farmers' participation in vaccination campaigns is reported to decrease by considering the side effects of vaccination such as abortion, decrease in milk production for a few days after vaccination, and animals becoming sick (25). This indicates a need to explain the side effects of vaccine to avoid mistrust and increase the uptake. In addition, presenting the results of economic studies showing the benefits of disease control programs are likely to motivate smallholders for their participation.

Although in this study a positive net economic impact of 76.4 TL/cow was revealed under the proposed vaccination scheme, there may be some debates about its feasibility due to limited human resources. In Turkey, FMD vaccine campaigns are applied by the state veterinary service. However, in regions where human sources and transportation availability are limited, vaccine application could also be done by private veterinarians besides state veterinarians. Furthermore, increasing the frequency of vaccination in order to close the immunity gap will require a higher number of FMD vaccine to be produced. Therefore, optimization studies focusing on vaccine production, storage, delivery, and accounting for changes in the FMD incidence rate are essential to further support our findings.

One limitation of this study was that epidemiological parameters for the vaccination scenario could not be obtained by conducting a field study. Hypothetically, current epidemiologic parameters for the year 2018 were multiplied by the relative risk ratio (17).

CONCLUSION

The partial budget analysis revealed that increasing vaccination frequency would result in a positive net economic impact of 76.4 TL/cow for farmers. Therefore, controlling FMD outbreaks signifies a socioeconomic gain to farmers that could improve participation in disease prevention programs. This study provides additional information for policy makers in order to adjust their FMD control strategy in border cities, taking into account regional variation in infection rates. Further studies are recommended, focusing on alternative FMD control strategies by using more comprehensive epidemiological and financial data throughout the country.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are publicly available. This data can be found here: https://www.oie.int/.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because related data was obtained through OIE-WAHIS system which is available to public use. This was stated in the manuscript.

AUTHOR CONTRIBUTIONS

NO and BV designed the study and reviewed the results. NO and OK contributed to data access. All authors has been read, approved, and contributed to analyses.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2020.557190/full#supplementary-material

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Revisiting the Economic Impacts of *Eimeria* and Its Control in European Intensive Broiler Systems With a Recursive Modeling Approach

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Ionophore compounds active against *Eimeria* species are widely used in intensive broiler systems and have formed the backbone of coccidiosis control for almost 50 years. Producers, however, are under pressure to reduce ionophore use due to consumer concerns over antimicrobial usage in food animals, and antimicrobial resistance. Moreover, current vaccines against *Eimeria* are commonly considered to be less cost-effective in intensive broiler systems, especially in Europe where attenuated live vaccines are used. An economic assessment of the impact of *Eimeria* and the disease coccidiosis, including the cost implications of different efficacies of control, is therefore timely to provide evidence for industry and policy development. A mechanistic model of broiler production under varying infection and control states was used to construct a dataset from which system productivity can be measured. Coccidiosis impact increased rapidly as control efficacy decreased. In the total absence of control, median impact was found to maximize at between €2.55 and €2.97 in lost production per meter squared of broiler house over a 33 day growing period. Coccidiosis remains a major risk to intensive broiler systems and the model developed allows investigation of issues related to coccidiosis control, antimicrobial use and the development of antimicrobial resistance.

Keywords: ***Eimeria*, coccidiosis, broiler, disease control, model, economics, impact**

INTRODUCTION

Coccidiosis is recognized as one of the principal intestinal disorders in intensive broiler production systems, limiting bird growth, and the efficiency of feed conversion (1). Caused by organisms of the genus *Eimeria*, there are three main species that account for most coccidiosis in broilers: *Eimeria acervulina*, *Eimeria tenella*, and *Eimeria maxima*. They are globally ubiquitous, with the most common of these, *Eimeria acervulina*, reported to have prevalence estimates in excess of 90% in some flocks (2–4). Furthermore, in addition to coccidiosis, *Eimeria* infection is a known risk factor for secondary infections and enteric dysbiosis, including necrotic enteritis (5, 6).

Infection occurs following the ingestion of sporulated oocysts from the environment, and proceeds through several phases of parasite asexual and sexual reproduction within epithelial cells of the digestive tract, after which the next generation of oocysts are excreted in the feces, where they sporulate to complete the life-cycle. The morbidity and mortality effects on the host are highly dependent on the infecting species, the infectious dose to which chickens are exposed (7) and the age at which infection first takes place (8). Induction of host protective immunity after recovering from infection varies considerably depending on the infecting species and the breed of chicken. In some cases, several cycles of infection and excretion may be required for full immunity to develop (9–11).

Ionophores are compounds that form complexes with specific ions and facilitate their transport across cell membranes. They are biologically active against both *Eimeria* and gram-positive bacterial species, are widely used in intensive broiler systems, and have been the backbone of coccidiosis control for almost 50 years (12). Field isolates of *Eimeria* species invariably have high levels of resistance to commonly used ionophores and also to many of the chemical coccidiostats (13–15), and it is very common for producers to use these different classes of drugs in rotation and shuttle programmes to minimize the impacts of drug resistance (16, 17). Interestingly, despite significant reductions in their efficacy, the ionophores continue to provide reasonable protection against clinical coccidiosis, and the accompanying growth and replication of resistant parasites, which can reach high levels in some flocks, allows for the host immune system to develop an effective and protective response (18).

Recent changes in society threaten to disrupt the status quo. Producers are under pressure to reduce the use of antimicrobial products in food animals, and the polyether ionophores, which are naturally produced by *Streptomyces* species, are included in this drive. While having no antimicrobial use in human health, they are classified as antibiotics in the United States of America and in 2018 more than 50% of total USA broiler production came from "antibiotic free" systems (19). This is reflected in a significant reduction in ionophore usage in the USA broiler industry, and a concomitant increase in the use of live coccidiosis vaccines (16). In Europe ionophores are classed as feed-additives, not antibiotics, nevertheless regulatory change affecting their use in livestock remains a distinct possibility (20). Any such policy decisions should to be supported by an evidence-based understanding of the impacts such reductions or bans on ionophore usage will have on food production systems. There is some evidence already emerging of the animal welfare consequences of removing certain critical antibiotics from intensive livestock systems (21), however the economic consequences are less clearly documented.

It is therefore opportune to assess current evidence on the impact of coccidiosis and the economics of its control in intensive broiler systems. In terms of economic impact, figures in the billions of dollars at the global level are often cited, extrapolated from the studies of Williams (1) in the United Kingdom. While much work in the past has been done to define coccidiosis impact under experimental conditions (22), assessing the impact of this disease from field data is complicated by many management, environmental (23, 24), and bird-level variables (25), necessitating large and detailed data sets. Although these kind of datasets exist in private companies, they are relatively inaccessible for reasons of commercial sensitivity. These facts, and the welfare implications of conducting *in vivo* experiments, have resulted in the development of *in silico* models to study coccidiosis in poultry systems.

The development of coccidiosis modeling has reflected the complexity of disease progression and pathogenesis. Parry et al. (26) described a recursive mathematical model of the *E. tenella* life cycle focused on tracking the development of immunity. Henken et al. (27, 28) took a similar recursive approach to assess the economic impact of differing levels of environmental contamination with *E. acervulina* on broiler production systems. Johnston et al. (29) expanded the modeling approach to *E. maxima* and *E. praecox,* focusing on the variation in replication rates of the parasite dependent on infectious dose. Further analysis by Klinkenberg and Heesterbeek (30, 31) explored the within host and between-host dynamics of *Eimeria* infection.

This paper presents an updated recursive model of *Eimeria* infection which permits the economic analysis of new developments in coccidiosis control. The model has application in the evidence-based assessment of policy and regulatory options, at a time when the use of antimicrobial products in food animal production systems is appearing increasingly unsustainable. With the specific focus on control, the model development was aimed to permit the following objectives:

1. To allow production parameters to be adjusted to reflect the different finishing and thinning weights found in intensive broiler systems.
2. To include models of infection for the three *Eimeria* species considered most common in intensive broiler systems: *E. maxima*, *E. acervulina*, and *E. tenella*.
3. To account for cumulative infection pressure, dose-dependent response to infection, and sub-clinical effects commonly observed in the field.
4. To incorporate immune dynamics at bird-level, allowing the simulation of vaccine-based control.
5. To allow control efficacy to be adjusted within and between production cycles for the investigation of shuttle and rotation programmes, drug resistance, and carry-over of infection between flocks.
6. To quantify the outcome of changes in coccidiosis control in economic terms at the level of the producer.

METHODS

Overview

A simulation model of broiler production was constructed in R (32). Upon loading the model, the production cycle parameters must be defined by the user, who provides the model with desired finishing and thinning weights for the chickens, the area (m^2) and number of broiler houses, and a maximum limit on stocking density (kg/m^2). The model then calculates optimal stocking density of day old chicks, estimates thinning and end days for the production cycle, populates broiler houses, and proceeds to run at single-day time steps. As the model proceeds, birds feed, grow, and ingest *Eimeria* oocysts from the environment. Pathogen replication is simulated within each bird, and further oocysts excreted to the environment increase the environmental infection pressure. This pathogen replication is linked to a reduction in the efficiency of conversion of energy into growth of birds. As birds are exposed to *Eimeria*, immunity develops, replication becomes less efficient, and pathological action on the host diminishes. Each of these relationships is described in detail.

The critical assumptions made by the model with respect to the pathology and dynamics of infection are:

- Infectious oocysts are distributed in a homogenous manner within the environment.
- Oocyst ingestion likelihood increases with increasing feed intake, and increasing environmental concentration.
- The lifecycle of each *Eimeria* species following oocyst ingestion proceeds at fixed time intervals.
- Intracellular lifecycle stages of *Eimeria* cause cell damage in the host that produces the pathology associated with infection.
- Cell damage recovers after 8 days.
- Increasing the infectious dose of *Eimeria* produces more severe pathology.
- Each species of *Eimeria* has a defined maximal reproductive capacity in terms of oocysts excreted per oocyst ingested by the host.
- This reproductive capacity is determined by the product of reproductive rates across the asexual and sexual lifecycle stages of the pathogen.
- Reproductive capacity plateaus with increasing cell damage, while pathology increases in severity.
- Immunity is generated by the extracellular transition between intracellular lifecycle stages, on a 4-day time delay.
- Chemical or ionophore control of infection is based on a reduction in the rate of transition between intracellular lifecycle stages.

These assumptions, and how they are conceived within the model, are discussed in detail below.

Bird Feeding and Growth

Published performance standards for as-hatched chicks, averaged across two well-known breeding lines (Ross 308 and Cobb 500) were obtained (33, 34). These data provide daily feed intake by mass, bodyweight gain, and total body weight in daily increments from hatching to ∼70 days age/5.5 kg bodyweight according to a specified metabolizable energy (ME) feeding schedule. From these data, the following series of relationships were described by models fitted using Levenburg-Marquardt algorithm to recreate as-hatched performance standards:

- Bodyweight by age (days) (BW model)
- Daily feed intake by bodyweight (FI model)
- Weight gain by ME intake (Growth model)

Levenburg-Marquardt is an algorithmic process for fitting models to data by minimizing the sum of squares (35), and is the most widely applied method when a non-linear relationship has been specified (36). Model fitting was performed in R, using the *minpack.lm* package (37).

Laird-Gompertz growth curves have been used to describe chicken growth in the past (38–40), and a function of this form was applied here to describe the relationship between time and body weight (BW) in growing chickens. The BW model defines bodyweight W, at time t as a function of time and bodyweight at $t = 0$, and the constants ν and α such that:

$$W_t = W_0 \, e^{\left(\frac{\nu}{\alpha}\,\left(1-e^{-\alpha t}\right)\right)}$$

This relationship is used within the model to predict the minimum age in days at which chickens attain target thinning and final weights in the absence of any impediment on growth. This sets the upper time limit of the model run. The maximum number of chickens in the house on thinning and end days is then calculated and the required thinning proportion to allow the stocking density to remain within the upper bound is calculated automatically, accommodating for a user-defined expected mortality rate.

Birds are placed in the house as day old chicks of mass 0.0565 kg, and feeding commences at daily increments. The FI model relates feed consumption as a function of the bird's current body weight, following the form:

$$I_t = \rho + \tau\left(1 - e^{-\sigma W_t}\right)$$

The intake of feed I at time t follows a decreasing exponential of bodyweight W at time t at rate $-\sigma$. The constant ρ improved the fit of the curve at initial values, while τ represents the maximal asymptotic value of I. Following from this, the model calculates the daily potential for growth of the bird in response to feed intake by referring back to the feeding schedule. The model for growth follows that of Zuidhof et al. (41), where growth is a function of metabolizable energy intake:

$$G_t = \frac{(1 - L)(I_t \times ME_t) - \delta W_t^{\varepsilon} - RFI}{\vartheta}$$

Where G is weight gain at time t, ME is the metabolizable energy content of the feedstuff at time t, δW_t^{ε} is the maintenance energy requirement for a bird of given body mass (W) at time t, RFI (the residual feed intake), δ, ε, and ϑ are constants. To relate infection status to growth rate, L is a variable coefficient representing the malabsorption of nutrients caused by *Eimeria* infection. The model records the total feed consumption at flock level, and the total output mass of chickens at thinning and finishing time. The parameter values applied for the model are given in **Table 1**.

TABLE 1 | Parameter values for bird growth and feed consumption models.

Parameter	Value	References
δ	200.079	Model fit
RFI	−44.63	
ϑ	3146.14	
ε	0.75	(41, 42)
ρ	0.013	Model fit
τ	0.258	
σ	0.552	
α	0.045	
ν	0.224	

Feedstuff was scheduled according to the recommendations of the breeding companies, with starter feed on days 1–10, grower feed on days 11–24, and finisher feed on days 25+. The ME content was defined as 3,000, 3,100, and 3,200 kcal/kg for these three feed types, respectively.

Eimeria Lifecycle

The model *Eimeria* lifecycle (**Figure 1**) followed the foundational structure developed by other authors (26, 28–30). In short, a recursive system of calculations operating at one-day time steps estimates daily change in pathogen lifecycle stages (x) in a

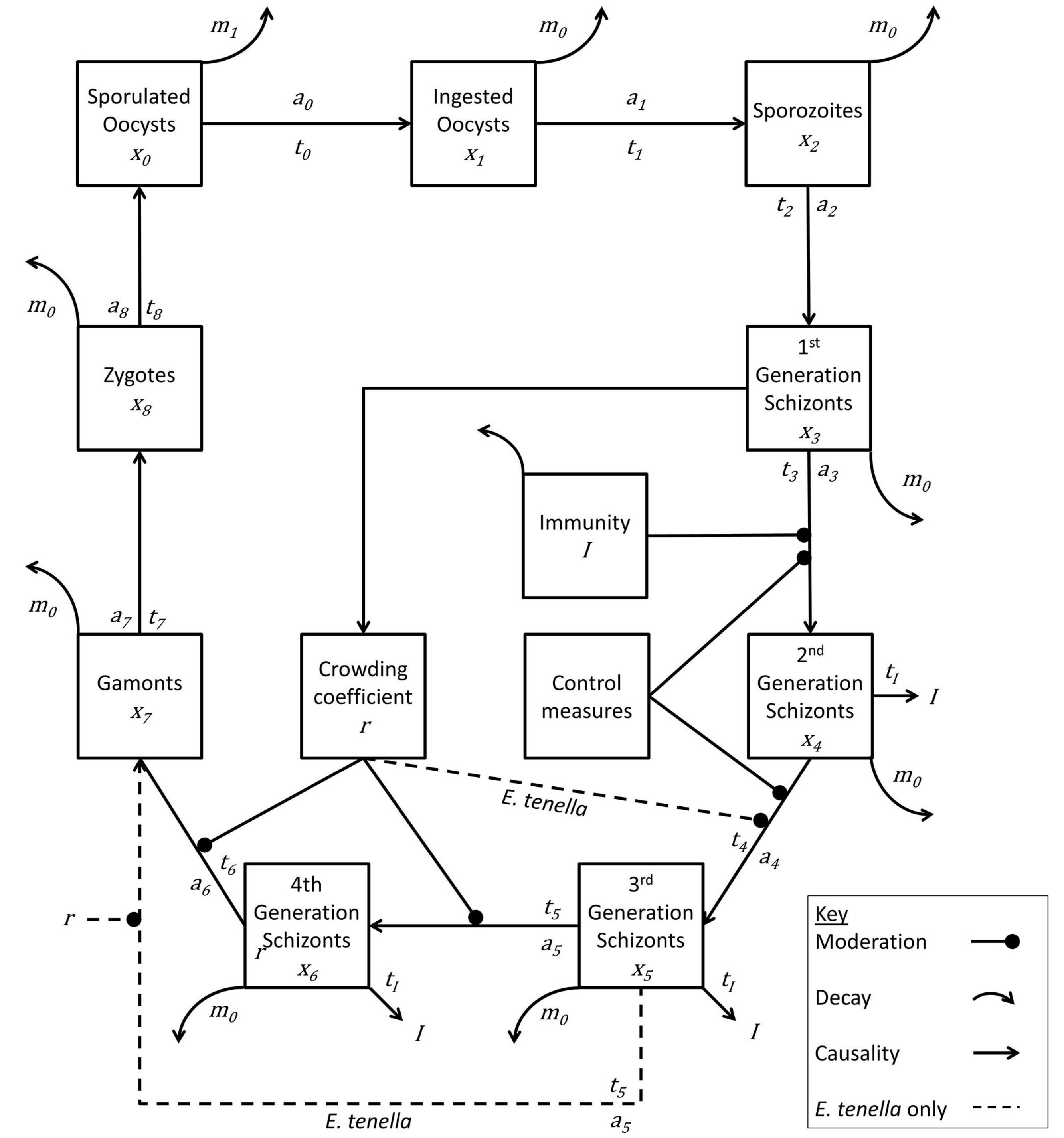

FIGURE 1 | Lifecycle of *Eimeria* species. Life cycle stages are denoted by x_n. Rate of advancement between stages is determined by coefficient a_n. The time lag between each stage is represented by t_n. Removal of pathogen from the system is indicated by m_n. Immunity generation is indicated by *I*. *Eimeria tenella* has one fewer lifecycle stages, and proceeds directly from x_5 to x_7.

deterministic manner at the level of the chicken and the level of the house, where each species of *Eimeria* has a number of developmental stages (i). The time interval in days between lifecycle stages (t_i), the replication rate between stages (a_i), and daily natural pathogen mortality (m) is specified for each lifecycle stage and for each species of *Eimeria.*

While detailed accounts of such models can be obtained within the literature, essentially the number of new *Eimeria* of life cycle stage $x_i$at time t can be calculated from the number at stage x_{i-1} at time $(t\text{-}t_{i-1})$. Similarly, the number of *Eimeria* of life cycle stage $x_i$leaving the lifecycle stage at time t can be deduced from the number new x_i at time $(t\text{-}t_i)$, therefore recording a net change in each compartment at each time step:

$$\frac{\partial x_i}{\partial t} = New\ (x_{it}) - New\ \left(x_{i(t-\ t_i)}\right)$$

Establishing a lifecycle framework for each species of *Eimeria* allowed the interpretation of published experimental results using a deterministic structure where the dynamics and pathology of infection are interpreted with reference to the passage of the pathogenic organism through its lifecycle. Such experimental studies include investigations of single dose and repeated dose effects on weight gain and mortality, within-pen transmission rates, immunogenicity of single dose and repeated dose infection, and diminishing returns on increasing single-dose infections. These relationships are described in detail below.

The baseline replication rate for each species of *Eimeria* was estimated from experimental and microscopic studies (43–48). These maximum replication rates were modified to fit dose-dependent oocyst output rates, the "crowding effect," shown in the results published by Williams (7). The pathogen lifecycle was modeled as a deterministic process in both time and replication rate such that oocyst excretion occurred at the time of peak excretion as observed *in vivo* (7, 49).

At each time step, environmental oocysts are inactivated at rate m_1, and within-host lifecycle stages suffer a mortality rate of m_0. All lifecycle parameters for *Eimeria* spp. are shown in **Table 2**.

Previous studies investigating total oocyst production and the pathogenic consequences of *Eimeria* infection have illustrated that while increasing the inoculation dose of oocysts increases the pathogenic action of the parasite, and initially increased the output of new oocysts from the host. A "crowding" threshold can be reached, however, at which point oocyst production plateaus or is diminished (7). The explanation for this phenomenon is not well-understood, appearing to result from an interaction of host cell availability, immune response and other factors (7, 29). In order to accommodate these two effects, an increase in pathogenicity with increasing pathogen load, whilst simultaneously inhibiting pathogen reproduction above a certain threshold, the crowding effect was emulated by an additional scaling coefficient in the reproduction rates of the final intracellular lifecycle stages for each species of *Eimeria.* In effect, this variable coefficient simulated a lack of host cell availability by taking into consideration the infection history of the individual bird. The number of first generation schizonts over time period h was used to define infection history. The duration of h was the duration of a complete cycle of intracellular infection summed with the time for cell repair, essentially a duration over which cell damage could be measured at time t. The number of new x_3 schizonts formed in this period was used as a measure for the infection history to provide a historic exposure variable x_E. For each species of *Eimeria*, the crowding coefficient was calculated to fit the reproductive rates estimated by Williams (7). For these results, $x_E$was back calculated from the experimental protocol, and plotted against the reduction in replication rate observed. Following selection of a functional form to fit the observed curves, parameters were estimated by non-linear regression. The replication coefficient at t was then calculated dynamically within the new model first by:

TABLE 2 | Lifecycle parameters for three *Eimeria* species, with reference sources.

Parameter	*Eimeria acervulina*	*Eimeria maxima*	*Eimeria tenella*	References
a_0	α {oocyst concentration, feed intake}			
a_1	8	8	8	(43–48)
a_2	1	1	1	
a_3	16	24	100	
a_4	16	12	160	
a_5	16	12	20	
a_6	12	12	N/A	
a_7	0.95	0.95	0.95	(50)
a_8	0.7	0.7	0.7	(26)
t_0	Variable with ingestion rate			Model fit to data (7, 49)
t_1	0 days	0 days	0 days	
t_2	1 day	1 day	1 day	
t_3	1 day	1 day	1 day	
t_4	1 day	1 day	1 day	
t_5	1 day	1 day	2 days	
t_6	1 day	1 day	N/A	
t_7	0 days	1 day	1 day	
t_8	0 days	0 days	2 days	
m_0	0.08	0.08	0.08	(27)
m_1	0.11	0.11	0.11	(26, 51)

$$x_E = \sum_{t-h}^{t} x_3$$

And then:

$$r = \sqrt{\frac{r_{\max}}{1 + e^{-k(Logx_E\ -\ E_0)}}}$$

Where r_{max} is the maximal value of r, k is a rate constant and E_0 is the value of $Logx_E$ at the inflection point. Parameter values are listed in **Table 3**.

TABLE 3 | Parameters for pathology, immunity and replication for each *Eimeria* species modeled.

	Parameter	*E. tenella*	*E. acervulina*	*E. maxima*	References/ data source
Pathology	β	2.295	0.434	0.716	Model fit (52)
	γ	18.879	21.058	19.942	Model fit (52, 53)
	η	0.947	0.947	0.947	(31)
Immunity	κ	0.000037	1×10^{-7}	0.001896	Model fit (9–11, 54)
	ζ	0.00013	0.000191	0.000034	
	a	5.606	2.568	10.000	
	b	0.575	0.316	0.882	
	c	170,999	16.379	62.609	
	t_Y	4	4	4	(55)
Replication	r_{max}	0.158	0.069	0.212	(7)
	k	−1.153	−0.758	−0.775	
	E_0	10.107	12.860	8.541	
Infection	Litter portion	2.66×10^{-6} kg			
	Litter intake		Triangular (0, 0.005, 0.03)		

Infection

An environmental seeding rate for *Eimeria* oocysts of each species is provided to the model at the initiation of the model run. This is defined as oocysts per meter squared of broiler house. The rate at which chickens ingest environmental oocysts was back-calculated from the mean of results observed in floor-pen transmission studies by Velkers et al. (49). These results were adapted to fit with the pathogen replication model already described. First total oocyst excretion observed was placed within a deterministic time structure by assuming all oocysts are excreted on the day of peak excretion. From this, the timing and quantity of infectious dose were calculated from oocyst excretion results, using the pathogen replication model described above. With floor space and litter mass recorded within the experimental protocol, it was assumed oocysts were distributed homogenously within the litter mass, and thus a quantity of litter equal to that containing the infectious oocyst dose was ingested. This calculation led to the division of the litter into a number of "portions" that can be ingested by the broilers. A single litter "portion" was estimated to be 2.66×10^{-6} kg. The rate at which these portions are ingested was then calculated as a proportion of total feed intake, such that a dimensionless variable for litter as proportion of total diet was defined as a triangular distribution with minimum at zero, modal value at 0.005 and maximum at 0.03.

At each time step in the model, the total number of sporulated oocysts in the broiler house is divided by the total number of litter portions remaining to estimate the oocyst concentration per portion in the environment. Each bird draws from the triangular distribution and this number is multiplied by the bird's feed intake for the day to obtain a mass of litter consumed. This number is then divided by the portion size and rounded to the nearest integer to provide a number of portions consumed (n). Bird oocyst ingestion is then estimated as the sum of n samples from a Poisson distribution where λ is the expected oocyst count per portion. This process was repeated for each species of *Eimeria* present in the environment.

Pathogenesis

Pathogenesis was modeled as arising from intracellular lifecycle stages (x_3 to x_7) of pathogen replication, which it was assumed resulted in lesion formation and malabsorption of nutrients from the gut lumen (56, 57). Malabsorption was represented by an additional variable coefficient (L) added to the growth model.

$$L = \frac{1}{1 + e^{-\beta(Log x_s - \gamma)}}$$

Where x_s at time t is the sum of intracellular lifecycle stages (x_3 to x_7) between t - 8 and t, representing an 8-day period taken for the gut to heal.

$$x_s = \sum_{t-8}^{t} \sum_{i=3}^{7} x_{it}$$

The model for each species was fitted by Levenburg-Marquardt algorithm to the mean of experimental results published by Conway et al. (52) who present dose-dependent response to infection for each species by measuring changes in bodyweight gain at 7 days post-infection. The proportion of growth lost relative to uninfected controls over a 7-day experimental period described by Conway was assumed to be derived from the bird growth and pathogen replication models already estimated above, allowing a relationship between infection status and growth to be defined. Since each of these species of *Eimeria* inhabit different regions of the gut, it was considered likely that coinfecting species would not compete directly with one another and were therefore likely to produce a cumulative impact on weight gain. In the absence of significant volumes of literature on coinfection effects, response was assumed simply to be additive when simultaneous infection with multiple species occurs.

Immunity

Immunity *(Y)* develops following the model proposed by Klinkenberg and Heesterbeek (30). The constants κ and ζ moderate the amount of new and proliferative immunity, respectively, subject to a time delay (t_Y), while existing immunity decays at rate η. The values for these constants estimated by Klinkenberg and Heesterbeek were modified to reflect the different pathogen replication rates assumed within the model here. Immunogenicity was derived from the transitions between stages x_3 and x_6 inclusive. Grouped together these are termed x_Y. The effect on immunity is delayed and occurs at $(t + t_Y)$.

$$x_Y = \sum_{i=4}^{6} New(x_{i(t-t_Y)})$$

For each species of *Eimeria*, immunity is independent. Immune level is a recursive calculation:

$$Y_t = \eta Y_{t-1} + \kappa x_Y + \zeta x_Y Y_{t-1}$$

This formula allows the generation of immunity following single or repeat exposure to pathogen to be expressed quantitatively as a single variable.

To translate this variable into action, a function *f(Y)* was derived for each species of *Eimeria*. A collection of published experimental results (9–11, 54) provided the data for this estimation. For each published experimental protocol (*Eimeria* species, dose schedule), *Y* was calculated, as well as the level of inhibition of pathogen replication, measured as reduction in fecal oocyst count. This relationship was visualized and observed to approximate an asymmetric sigmoidal curve. A five-parameter logistic function with asymptotes at zero and one provided a form that was defined for each *Eimeria* species by non-linear least squares. This functional form is used when an asymmetric dose-response relationship is observed (58, 59).

$$f(Y) = \frac{1}{1 + \left(\left(\frac{Y}{c}\right)^b\right)^a}$$

Host immunity effect on the pathogen was expressed as a moderating coefficient in the transition of stages x_3 to x_4. Pathogenicity and immunity parameters are listed in **Table 3**.

Control

To establish a baseline scenario for coccidiosis control, commonly applied ionophore and combination (ionophore plus chemical) coccidiostats were reviewed for their means of activity against *Eimeria* lifecycle stages. Nicarbazin-Narasin prevents the formation of sporozoites and merozoites. Salinomycin is shown to attack the extracellular merozoite stages of the pathogen lifecycle while sporozoites may be sufficiently resistant to allow host-cell invasion (60), although this may depend on the concentration of salinomycin to which the parasite is exposed and the exposure time (61, 62). In the model therefore, the action of control was simulated by assigning a control efficiency value *(C)* ranging between 0 and 1. Control action was divided between the development of new x_4 and x_5 generations by multiplying by (1-$\sqrt{C}$). This allowed the model to simulate the suppression of clinical disease by limiting intracellular lifecycle stages and reduction in oocyst excretion but also allowing immunity to develop.

The new oocyst formation functions in each compartment for *E. acervulina* and *E. maxima* are summarized:

$$New(x_{it}) \begin{cases} x_{8\,(t-t_8)} \times a_8 \times \left(1 - m_0^{t_8}\right), & i = 0 \\ \propto \{\textit{environmental oocyst concentration, feed intake}\} & i = 1 \\ x_{1\,(t-t_1)} \times a_1 \times \left(1 - m_0^{t_1}\right), & i = 2 \\ x_{2\,(t-t_2)} \times a_2 \times \left(1 - m_0^{t_2}\right), & i = 3 \\ x_{3\,(t-t_3)} \times a_3 \times \left(1 - m_0^{t_3}\right) \times \left(1 - \sqrt{C}\right) \times (1 - f(Y)), & i = 4 \\ x_{4\,(t-t_4)} \times a_4 \times \left(1 - m_0^{t_4}\right) \times \left(1 - \sqrt{C}\right), & i = 5 \\ x_{5\,(t-t_5)} \times a_5 \times \left(1 - m_0^{t_5}\right) \times r, & i = 6 \\ x_{6\,(t-t_6)} \times a_6 \times \left(1 - m_0^{t_6}\right) \times r, & i = 7 \\ x_{7\,(t-t_7)} \times a_7 \times \left(1 - m_0^{t_7}\right), & i = 8 \end{cases}$$

And for *E. tenella* one fewer schizont stages:

$$New(x_{it}) \begin{cases} x_{8\,(t-t_8)} \times a_8 \times \left(1 - m_0^{t_8}\right), & i = 0 \\ \propto \{\textit{environmental oocyst concentration, feed intake}\} & i = 1 \\ x_{1\,(t-t_1)} \times a_1 \times \left(1 - m_0^{t_1}\right), & i = 2 \\ x_{2\,(t-t_2)} \times a_2 \times \left(1 - m_0^{t_2}\right), & i = 3 \\ x_{3\,(t-t_3)} \times a_3 \times \left(1 - m_0^{t_3}\right) \times \left(1 - \sqrt{C}\right) \times (1 - f(Y)), & i = 4 \\ x_{4\,(t-t_4)} \times a_4 \times \left(1 - m_0^{t_4}\right) \times \left(1 - \sqrt{C}\right) \times r, & i = 5 \\ x_{5\,(t-t_5)} \times a_5 \times \left(1 - m_0^{t_5}\right) \times r, & i = 7 \\ x_{7\,(t-t_7)} \times a_7 \times \left(1 - m_0^{t_7}\right), & i = 8 \end{cases}$$

Production and Economic Parameters

On running, the model records bird weight, mortality, and feed consumption per day over the course of the production cycle. On the estimated finish date, the total mass of extant chickens is recorded as system output, as is the total feed consumed. These data provide a point at which economic analysis of the production system can be performed.

To test the application of the model, production parameters exemplifying a typical European broiler-production system were selected and run through the model (**Table 4**). The production parameters were devised with the collaboration of European national producer associations who wished to remain anonymous. With data on precise input costs being commercially sensitive, a range of prices was applied to quantify producer margins over feed costs, expressed as Euros (€) per meter-squared.

In the absence of data from the field on environmental oocyst concentrations at the beginning of the production cycle, the model was tested with fixed initial oocyst concentrations. To introduce disease into the system, the model was run 350 times with starting levels of *Eimeria* spp. oocysts from 0 to 5,000/m^2 (0, 50, 500, 50,00) for each species. Given that the efficacy of control measures in the field is known to be variable, but of uncertain distribution, control efficacy was fixed at a range of levels across the distribution from 0 to 100% (0, 25, 50, 75, 100). Each model run simulated 1,200m^2 of floor space, equivalent to 27,700 birds. Across 350 model runs, this generated a total simulation of 420,000 m^2 of floor space and 9.7 m chickens.

TABLE 4 | Production and economic parameters used to simulate intensive broiler production, selected to be representative of a typical European system.

Production parameter	Value	Unit
Finishing target weight	1.9	kg
Finish time	33	Days
Thinning of flock	No	–
Thinning weight	N/A	kg
House size	1,200	m^2
Stocking density limit	42	kg/m^2
Chick placements	27,714	chicks
Base mortality rate	4.2	%
Condemnation rate	1.08	%
Control schedule	1–33	Days
Feed price	270–320	€/ton
Output price	0.82–0.9	€/kg
Starter ration	3,000	kcal/kg
Grower ration	3,100	kcal/kg
Finisher ration	3,200	kcal/kg
Control efficacy	0–100	%

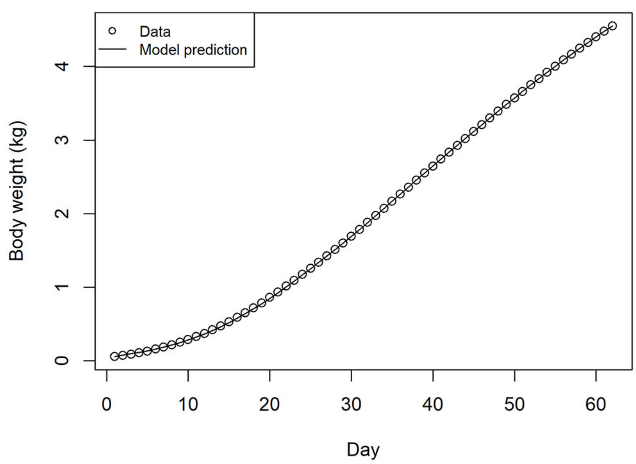

FIGURE 2 | Source data and recursive growth model fit for bird weight over days of production, estimated from feed intake, feed schedule, and energy conversion models.

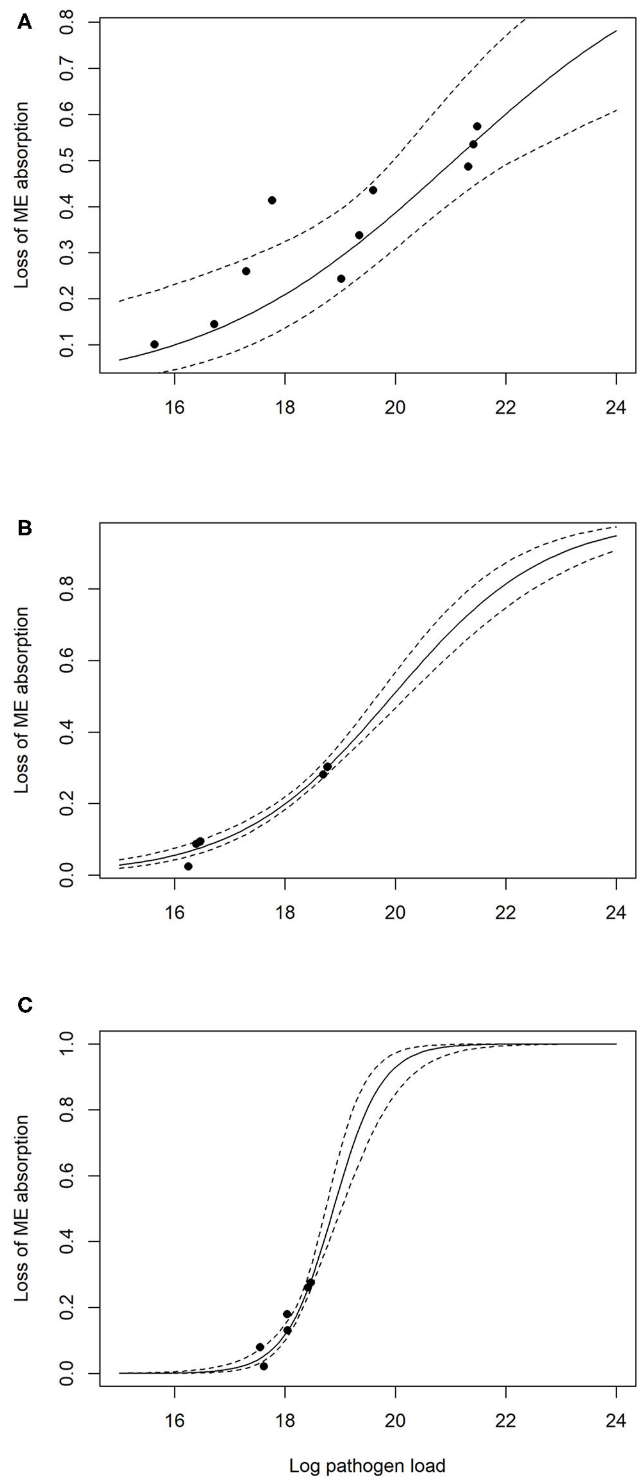

FIGURE 3 | Pathogen influence on reduction in metabolizable energy (ME) absorption from the gut, lines show the mean and 95% CI of model prediction, with source data indicated by point: **(A)** *Eimeria acervulina*, **(B)** *Eimeria maxima*, **(C)** *Eimeria tenella*.

RESULTS

The fit of the model simulation for broiler growth in the absence of infection was found to be extremely close to the source data when tested to day 63, far beyond the finishing age of commercial flocks typical in Europe (**Figure 2**). This output was produced from the sequential application of the feed intake model, the metabolizable energy content of the feed determined from the feed schedule, and the broiler growth model.

The output for the model of pathogenesis, shown as the reduction of absorption of metabolizable energy following infection for each of the three species of *Eimeria,* with reference points for source data, is presented in **Figure 3**. As expected, *Eimeria acervulina* shows the slowest increase in pathogenicity with increasing infectious dose, while *E. tenella* showed the most rapid increase. For illustrative purposes, models are extrapolated

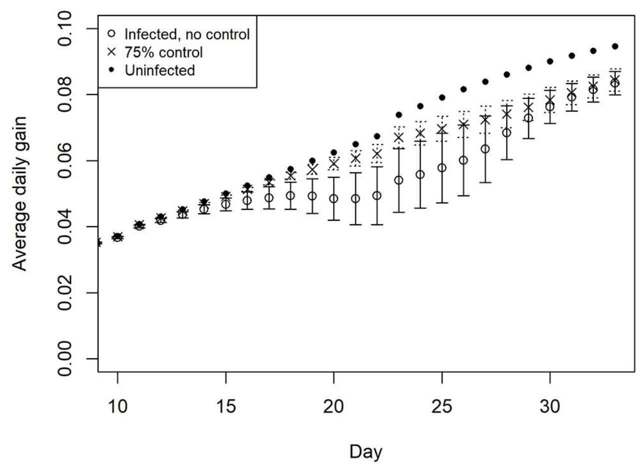

FIGURE 4 | Impact of multiple *Eimeria* species (*E. acervulina*, *maxima*, *tenella*) on average daily weight gain in simulated infected broiler flocks, with 95% distribution, with and without control.

outside of the source data range in this figure. Data points for calibrating models of severe infection of *E. maxima* and *E. tenella* were not found in the literature, due to high levels of mortality. Within the simulations, no additional mortality was observed within the flock simulation models at the oocyst seed levels tested.

The average daily weight gain of chickens within the simulated flocks for uninfected and infected status is illustrated in **Figure 4**. Growth begins to deviate from the expected trajectory after ∼2 weeks in the absence of control measures. The impact flattens growth for ∼7 days. There is also a notable increase in variation between chickens at this stage of the production cycle. With the addition of control, illustrated here at 75% efficacy, the flattening of growth is significantly less pronounced than in the absence of control, nevertheless a divergence from uninfected flock growth rates is predicted.

In the absence of control, full protective immunity to all three species is developed by day 20 on average. In the presence of increasing control efficacy, this development is slowed but not prevented, such that full protective immunity is delayed by an average of ∼7 days for all species at 75% efficacy of control (**Figure 5**).

Figure 6 illustrates the effect of infection and control on the efficiency of feed conversion in broiler flocks. This variation in results is generated by the variation in starting oocyst concentration and species present in each of the 350 simulations. The variation in outcomes across flocks was reduced with increasing efficacy of control. Between flock variation was extremely low when repeated model runs were made with equal initial oocyst concentrations at commercial flock sizes and stocking densities.

To analyze the economic impacts of *Eimeria* and its control, a range of prices were applied to feed and output. Particular attention was given to the lowest margin when feed costs are high, output prices low and financial risks to producers are therefore greatest, it was found that median margins of €12.18 per m^2

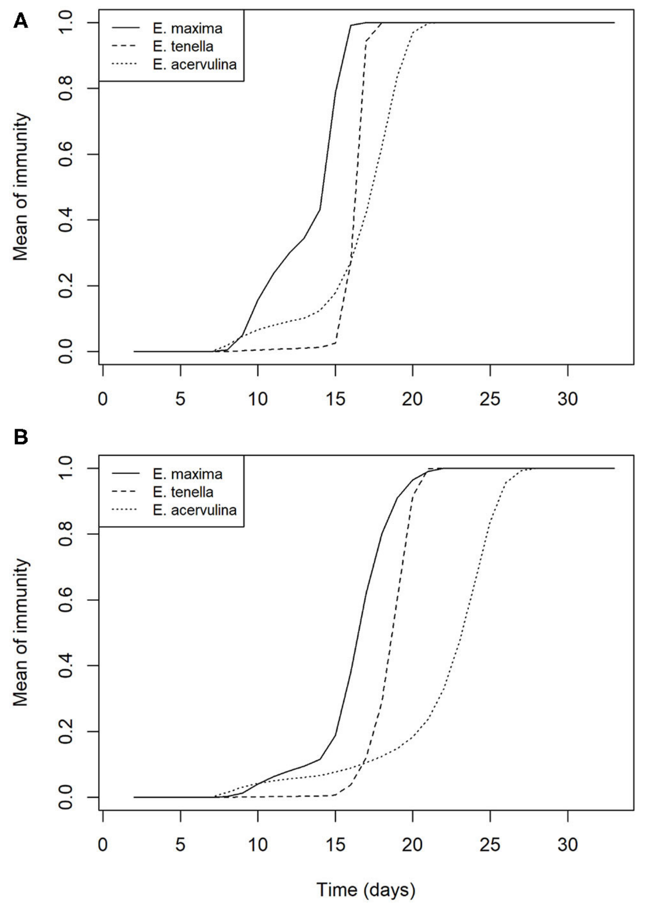

FIGURE 5 | Mean within flock protective immunity against *Eimeria* species **(A)** in the absence of control measures; and **(B)** with control of *Eimeria* at 75% efficacy.

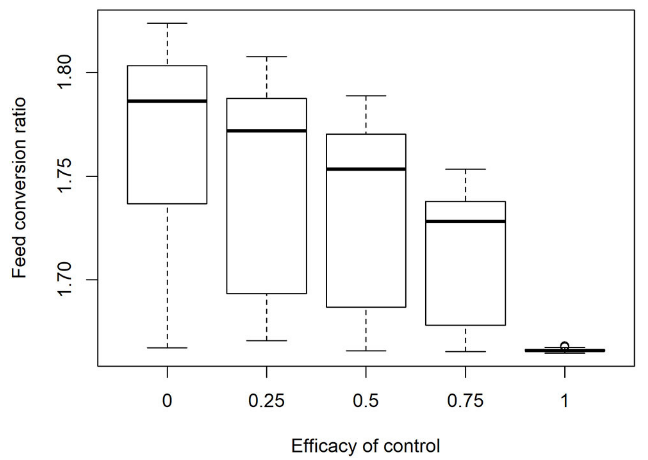

FIGURE 6 | Impact of increasing control efficacy and variable infection pressure on efficiency of feed conversion in 350 simulated commercial broiler flocks.

in the absence of disease are reduced to €9.63 at the median when control is completely ineffective, for a loss of €2.55 m^{-2} (**Figure 7**). A minimum of the margin distribution at <€9 m^{-2} was recorded in the total absence of control. Proportionally large changes were evident with relatively small changes in efficacy. The median impact of coccidiosis and changes in control efficacy across price ranges is presented in **Table 5**.

DISCUSSION

This paper presents a first iteration of a model for coccidiosis impact in intensive broiler production including multiple species of *Eimeria*. The three species are those most commonly associated with intensive broiler systems, and the impact shown in the model suggests that *Eimeria* species remain a significant source of financial loss even in the presence of typical control measures. The economic analysis demonstrated the potential for coccidiosis to cause further significant losses in the absence of control. Even at a relatively efficacious control level of 75%, the average loss across the range of infection pressures measured is approaching €1.50 per m^2 per flock.

At present, these results make are not considered representative of any particular national production system, since no assumptions were made with regard prevalence of each species, which could vary geographically, or initial oocyst concentration maintained within broiler houses after cleaning and disinfection protocols. These figures would need to be estimated for a stochastic simulation to look at national or regional losses to coccidiosis.

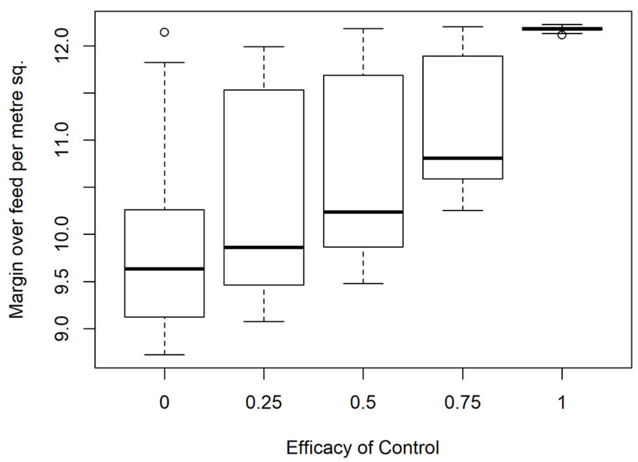

FIGURE 7 | Impact of *Eimeria* infection on producer margin over feed costs (€/m^2) under increasing levels of control efficacy and infection pressure in 350 simulated flocks.

The search for data on control efficacy through EFSA found field isolates of *Eimeria* species with significantly higher levels of resistance, reducing control efficacy below 50%. An efficacy of 75% would have placed at the upper limit of the EFSA figures. The non-linear increasing rate of loss as control efficiency decreases is an important consideration when any change in management where marginal decreases in control efficacy could result.

The current political and societal climate is such that in the near term, changes in available coccidiosis control options are possible as pressure mounts on the continuing use of antimicrobial products in livestock agriculture. The results presented here serve to illustrate the challenges that must be considered when new control measures are proposed as a replacement for ionophores. Producer margins are sensitive to relatively small changes in control efficacy.

This assessment of the cost of *Eimeria* infection is not complete however. Revenue foregone due to delays to production, the costs of reactive treatment and secondary infections and the cost of cleaning and disinfection procedures between flocks are not estimated. The model ends the production cycle on the planned day and harvests chickens at substandard weight, quantifying change in output as lost mass. In reality, producers could extend the production cycle, which alters the dynamic of production in terms of output per year and the spreading of fixed costs. Additionally, any medications applied in a reactive manner to severe cases are not accounted for or costed in the model, although through discussions with producers across Europe it was established that this is relatively common course of action. A further analysis of lesion score data from routine monitoring of poultry flocks would be a way to establish the criteria under which additional control products are applied. This would allow a management-simulating component, based on the behavior of the producer, to be designed.

The uncertainty in feed price represents fluctuations in the market price. While it is acknowledged that some seasonal fluctuations in pricing are predictable and producers can hedge against this by forward purchasing, the proportion of

TABLE 5 | Simulated changes in median producer margins over feed costs with varying price conditions and coccidiosis control efficacy in a typical European intensive broiler system.

		Median change in margin over feed (€/m^2 per flock)				
		Efficacy of control				
Feed price	Output price	100%	75%	50%	25%	0%
Low	High	0	−1.58	−2.25	−2.67	−2.97
Median	Median	0	−1.47	−2.10	−2.49	−2.75
High	Low	0	−1.37	−1.94	−2.32	−2.55

farms entering into such arrangements or the impact of these arrangements on the distribution of feed prices received by producers as a whole is not known. The lower margin, where feed prices are high and output prices low, was then analyzed as the condition of greatest financial risk for poultry producers. The model could be further adapted to include other variable input and output prices and fixed costs to produce detailed analysis of farm budgets.

A modeling approach to analyzing policy change can mitigate the need for *in vivo* studies with consequent risks to animal welfare. Access to larger and more comprehensive field datasets would allow a more robust approach to validating model outcomes where some parameters are approximations of secondary data. This is particularly relevant when the data used to define critical parameters such as effects on growth rate are derived from single *Eimeria* lines, or from genetic lines of chicken that are no longer farmed commercially.

The model output suggests *Eimeria acervulina* may be considered the most significant of the three species studied, possibly on account of its high prevalence and lower immunogenicity giving it a longer duration of action within the flock. A caveat would be that between-strain variation within each species is not considered here. Further data on field strains and the range of pathogenic outcomes displayed would help define what could be considered a typical infection within the model. The model of coccidiosis impact is informed by available literature data which quantified dose dependent responses. The limit of these data is evidenced by the number of comparison points in **Figure 3**. In reality, this represents a simplified view of the field situation where variations in pathogenicity and immunogenicity of different strains of *Eimeria* species and host genetics could interact to produce a wider range of potential outcomes. Across repeated model runs with the same initial settings, the flock level results were found to be extremely consistent. This is a product of the homogenous-mixing mode of environmental contamination, such that oocysts are spread evenly per meter-squared. Where the first infected birds in the production cycle produce thousands or hundreds of thousands of new oocysts, this model quickly produces similar infection patterns when flocks are of typical commercial size.

Individual chicken-level variation in response is expected (63), and can be included within the model framework. Studies such as Hamzic et al. (53) have sought to quantify bird-level variation as part of genome-wide association studies. These types of data, on large samples of modern commercial lines of broilers could be invaluable in developing models with a greater level of resolution.

The model is designed to allow successive flock placements, with associated cleaning and downtime periods, although these have not yet been parameterized. The relationship between contamination level at slaughter date, the use of ionophores to control oocyst production, downtime cleaning and disinfection protocols, the development of ionophore and other drug resistances, and the initial contamination level at the start of the next flock cycle has not yet been established within the model. With appropriate data, this should be feasible and indeed desirable. While the current simulations show economic benefits in the use of ionophores, benefits may diminish significantly unless shuttle and rotation systems are employed, and this could be an important consideration when alternative control methods are investigated in isolation.

Data on flock-to-flock carry-over of *Eimeria* oocysts are difficult to find in the public domain. Indeed, data on oocyst numbers in the environment over the course of the flock cycle are difficult to find for European systems. Some data are available for US systems [e.g., Chapman et al. (64)] which operate on deep litter, but these are not applicable when cleaning and disinfection occurs between each flock.

Within the model simulations, each flock was seeded with a relatively low initial environmental oocyst dose. The step-wise increase of oocyst concentration in the environment and the dose-dependent response curves defined meant that by the time sufficiently large quantities of oocysts were available to constitute potentially lethal doses, chickens had developed partial immunity through prior exposure. While mortality as a direct result of *Eimeria* infection has been discussed, the frequency with which this occurs in the field, and whether it is successfully disaggregated causally from other forms of dysbiosis for which *Eimeria* infection is a known risk-factor, is not well-documented. Further attention should also be paid to the speed of immunity development to each species, particularly *Eimeria tenella*. It may be the case that a more complex model of the dynamics of immunity is required to reflect differences between each species.

As a potentiator of secondary infection, coccidiosis is particularly associated with necrotic enteritis caused by *Clostridium perfringens.* This effect was not quantified within the model as the complexity of environmental and dietary factors in the etiology of this disease would necessitate significant assumptions to be made to avoid a large increase in computational load. It is a potential future development of this model.

Experimental studies have shown that coinfection with multiple species of *Eimeria* can result in modifications to pathology when compared to a single-species infection, however the exact nature of these modifications depends on the specific *Eimeria* species in question and for several species is not documented. During co-infection with two species (*E. praecox and E. acervulina*) Répérant et al. (65) show an additive effect on growth and FCR, with coinfection producing greater change than single species infection. Conversely, Jenkins et al. (66) show multiple species infection having a protective effect. As a proportion of non-infected controls, 48% of healthy weight gain was observed during *E. maxima* infection, 90% weight gain during *E. praecox* infection, and 79% during coinfection. From the perspective of pathogen reproduction, Williams (67) demonstrated a reduction in reproductive capacity of co-infecting species when *E. acervulina* infection occurs concurrently with any of four other species (*E. tenella*, *E. maxima*, *E. brunetti*, *E. necatrix*). This could be attributed to the broad effects of the innate immune response, and a central role for multiple cytokines including interferon gamma in the response to different *Eimeria* species (68). Humoral immune responses, however, have been shown to be independent and specific for different *Eimeria* species such that coinfection does not produce a synergistic or competitive effect on immunity (69). Resolving this relationship is likely to be dependent on timing, strain, dose, and host immune response and therefore is likely to require large amounts of field data, or significant *in vivo* studies with the welfare and ethical considerations that that would raise. As a result, within this study a simple additive effect was incorporated, with the acknowledged limitation that this could result in overestimation of the impact of infection in multispecies cases.

In summary, the further development of this model would allow analysis of policy-relevant questions with respect to broiler production in intensive systems. The current model output illustrates the continuing sensitivity of producer margins to changes coccidiosis burden and control efficacy in broiler systems. This must be considered in any future changes in production standards or legislation.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

DB, FT, and WG: conceptual work on *Eimeria* biology. WG, CB, and JR: conceptual work on modeling method. CB and JR: data collection with poultry producers. WG, CB, DB, FT, and JR: manuscript contribution. WG: model programming and analysis. All authors contributed to the article and approved the submitted version.

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Herd-Level Risk Factors for Swine Influenza (H1N1) Seropositivity in West Java and Banten Provinces of Indonesia (2016–2017)

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Swine could play a role as a "mixing vessel" for avian and human influenza viruses and should, therefore, be thought of playing an intermediate role in the emergence of pandemic influenza strains. The aim of this study was to identify risk factors for Swine influenza virus (SIV) seropositivity at the farm level in West Java and Banten provinces, Indonesia. A total of 649 blood samples were collected from 175 pig farms, and at the time of sampling, a questionnaire about routine herd management was administered to participant herd managers. Swine influenza virus serological status for each of the sampled pigs was tested using the IDEXX ELISA-test (Maine, US). The apparent herd-level prevalence of SIV seropositivity was expressed as a true herd-level prevalence using the Rogan and Gladen method, modified to account for low and high prevalence herds using a Markov chain Monte Carlo Bayesian approach. The association between herd-level characteristics and SIV seropositivity status was assessed using binary logistic regression. The true prevalence of SIV seropositivity was 26% (95% CI = 20–33). The presence of animals apart from pigs on farm (odds ratio, OR = 2.51, 95% CI = 1.0–6.0), keeping breeding sows for <2 years (OR = 5.9, 95% CI = 1.8–20), being <1 km from a poultry farm (OR = 2.4, 95% CI = 1.0–5.7), and purchasing pigs only through pig collectors (OR = 11, 95% CI = 4.3–29) increased the risk of a herd being seropositive to SIV. Our results show that biosecurity to limit the introduction of SIV should be enhanced on farms located in areas of high pig and poultry farm density. While the role that pig collectors play in the transmission of SIV warrants further investigation, swine producers in West Java and Banten should be made aware of the enhanced risk of SIV associated with purchasing of replacements from collectors.

Keywords: swine influenza virus, risk factors, seroprevalence, Indonesia, swine

INTRODUCTION

Swine influenza virus (SIV) infection is an acute and contagious respiratory disease of pigs (1, 2) that causes economic loss in commercial piggeries due to high morbidity (3, 4). In addition, the presence of swine influenza raises public health concerns because pigs can be infected by other pigs, poultry, or human influenza viruses at the same time, and this could potentially generate a novel pandemic strain (4–6). Although people who work in close contact with pigs have been reported to have an increased seroprevalence to SIV (7, 8), the incidence of SIV among humans has rarely been investigated.

Swine influenza is caused by an influenza type A virus that belongs to the Orthomyxoviridae family. Influenza type A viruses can be categorized based on their hemagglutinin and neuraminidase proteins. In pigs, influenza type A viruses are often detected as H1N1, H1N2, and H3N2 sub-types (9). One relatively stable subtype is H1N1, the etiologic agent responsible for most swine influenza outbreaks until the mid-1990s and historically associated with classical swine flu strains. The primary route of virus transmission is pig-to-pig contact, with the virus entering the body *via* the nasopharyngeal route, most probably through nose-to-nose contact or following direct contact with mucus.

Swine flu outbreaks have been reported in several parts of the world. In America, swine flu was first reported in the north and mid-west of the United States in 1918. However, the virus could only be isolated in pigs in 1930 (10). The classical SIV in Europe was first isolated during an outbreak that occurred in northern Italy in 1976 (10). Based on surveillance conducted in 2006 and 2007, swine flu has caused acute respiratory distress in pigs in Belgium, England, Italy, France, and Spain (11). Swine flu infections in humans caused by H1N1 and H3N2 subtypes were reported in Italy in 1993 (12). A serologic surveillance in Japan indicates that H1N1 subtype influenza infection has occurred in Asia since 1977 (13). In Southern China, isolation of the swine influenza H1N1 virus subtype was carried out in 1993 (14). In Indonesia, H1N1 influenza (the pandemic strain of 2009) was reported in April 2009 (15). The virus was detected at pig slaughterhouses in the province of Jakarta and on pig farms in Bulan island, in the province of Riau Islands, in 2009 (15). The 2009 epidemic of SIV in Indonesia was responsible for 1,005 confirmed cases and five deaths (15).

Information on SIV-related risk factors in pig farms is limited, although some studies have reported on some risk factors. A study in England indicate that keeping pigs indoor, high density of pigs per water space, and younger pig age (16) are potential risk factors for SIV infection in pigs. The existence of a pen partition between pens, uncontrolled entrance to the farm (17), and history of a respiratory illness of pigs (18) have been identified as risk factors for influenza seropositivity of pig farms in Spain and China. In addition, the size of the farm and the presence of other animals have been reported as risk factors for the spread of SIV among pigs in pig farms in Malaysia, the neighboring country of Indonesia (19).

Indonesia has reported large numbers of outbreaks of HPAI H5N1 in poultry since 2003 (20). While numerous epidemiological studies of HPAI H5N1 in poultry in Indonesia have been published (21–24), studies on the epidemiology of SIV are limited. We could locate only one field study of SIV that concentrated on estimations of seroprevalence (25). With this background, our aims were to describe the prevalence of SIV seropositivity among commercial swine herds in Java, Indonesia, and to identify the risk factors for SIV seropositivity. Better knowledge of the risk factors for SIV provides insight into farm-level and herd management characteristics that increase the risk of the disease.

MATERIALS AND METHODS

Study Area

The study areas were Banten and West Java provinces, bordering Jakarta (the capital city of Indonesia) where the highest number of human cases due to highly pathogenic avian influenza H5N1 (HPAI) were reported during 2005–2017 (26). During the HPAI outbreak, most of the poultry farms in both West Java and Banten were infected by the disease (27). Importantly, the two provinces supply pork meat to Jakarta. The number of pig farms in Banten province was 135 (4,823 pigs), with a density of 0.49 pigs/km^2, while the number of farms in the province of West Java was 310 (7,055 pigs), with a density of 0.199 pigs/km^2 (28). Apart from having pig farms, the provinces of West Java and Banten also have poultry farms, either commercial poultry or backyard type. The transmission of zoonotic SIV to humans is an important public health concern for the study areas.

Sample Size

Sample size determination was performed using ProMESA software, version 1.62 (EpiCenter, Massey University, New Zealand), aiming to detect the presence of SIV in a pig population based on a two-stage sampling design. The two-stage sampling was determined by calculating independently the number of herds from which the individuals will be sampled and the number of individuals per herd to include in the sample. Several parameters were defined for sample size calculation, including the total number of pig farms ($n = 445$), average number of pigs per farm ($n = 30$), minimum expected prevalence of positive herds (1.5%), and minimum expected prevalence of positive animals (50%). The output indicated that this study required at least 166 pig farms and at least four animals per farm to be sampled. On each farm, young and adult pigs were randomly selected for blood collection.

Study Design

This was a cross-sectional study conducted as part of a national pig disease surveillance program carried out by the Disease Investigation Center Subang within the Directorate General of Livestock and Animal Health Services of the Ministry of Agriculture, Indonesia. The study was carried out from February 2016 to November 2017 in two districts in Banten province (Tangerang, Tangerang City) and four districts in West Java province (Bogor, Bekasi, Karawang, and Kuningan; **Figure 1**).

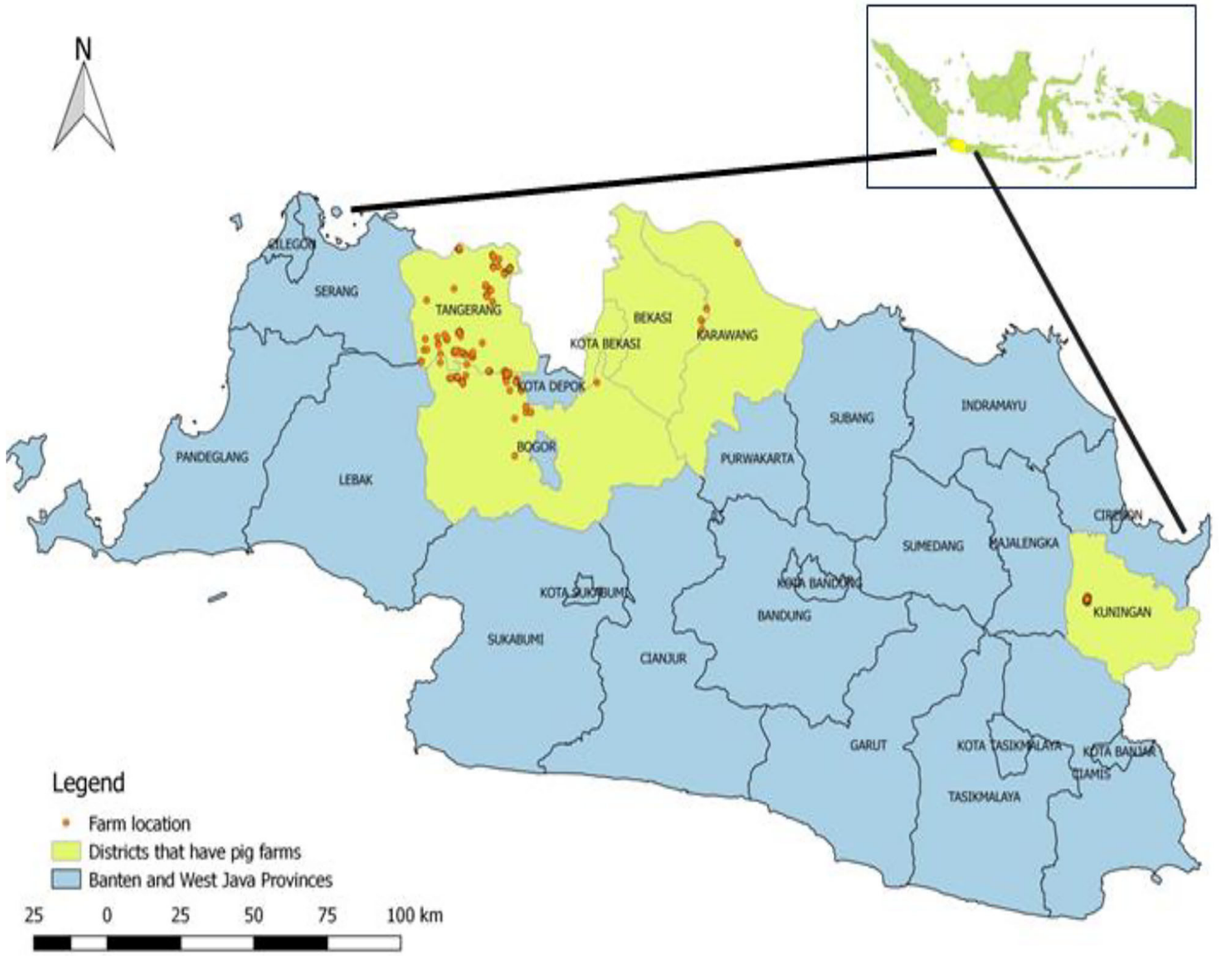

FIGURE 1 | Geographical map of the Republic of Indonesia and the study area including Banten province (Tangerang City, Tangerang) and West Java (Bekasi, Bogor, Karawang, and Kuningan). Districts where enquiries were conducted are yellow in color, and farms are represented as red, round dots.

The total number of swine farms in the study area was 445, of which 175 were selected for sampling.

On each farm, at least three animals (young and adult) were selected at random for blood collection. The number of pigs to be sampled was chosen to provide 95% confidence that at least one seropositive pig would be detected if the within-herd prevalence of SIV seropositivity was 50%. Samples were collected by jugular vein puncture using plain evacuated tubes (Vacuette, Dutscher SAS, Brumath, France). Sera were obtained by centrifugation for 10 min at 3,500 × g and stored at −20°C until testing.

Farm Data

At the time the farms were visited for sampling, a face-to-face interview with the herd manager was carried out using a standardized questionnaire. To ensure consistency in the way responses to questions were recorded, district officers who carried out the sampling and administered the questionnaire were trained on how to conduct an interview, clarify questions, and conduct operational procedures. All the herd managers that consented to having their pigs sampled agreed to take part in answering the questionnaire.

The questionnaire solicited details about general herd information, health management, and sources of pigs. The general herd information section of the questionnaire recorded details of farm location (the longitude and the latitude of the main farm shed were recorded by the district officer administering the questionnaire using a global positioning system), the type of herd, the reason for keeping pigs, the type of business (fattening/breeding), the length of time pigs were raised, herd management, use of personal protective equipment, details of biosecurity and farm access, and distance to the nearest residential area. Farm management details included the type of management system (intensive, free range/extensive), the type of buildings and cages used, the distance from the herd manager's

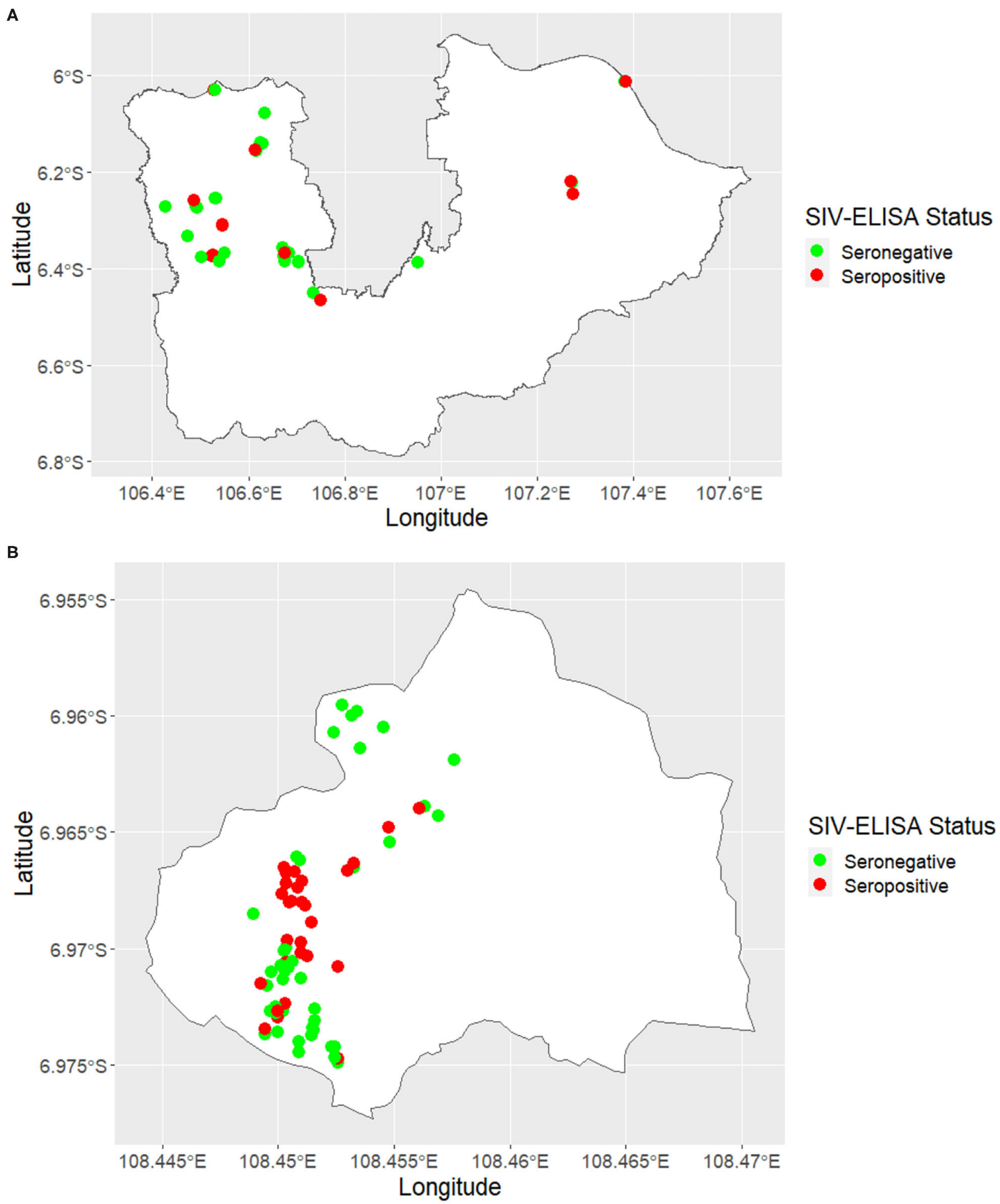

FIGURE 2 | Maps showing the location of swine influenza farm status classified by serological-test results in **(A)** Tangerang City, Tangerang, Bogor, Bekasi, and Karawang and **(B)** Kuningan.

home to the farm, the presence or the absence of other animals on the farm, the distance of the farm to the nearest commercial poultry farm, the type of feeders and waterers in use, the presence or the absence of slaughter facilities within the farm, the number of animals of different age classes present, and information relating to waste management. The health management section of the questionnaire included questions about the presence or the absence of a vaccination program, the presence or the absence of a worm control program, and information relating to the frequency of disease events during the 3-month period immediately prior to the administration of the questionnaire. Questions about the source of pigs included the origin of replacement gilts and boars, the destination of pigs that were sold, and the method of transport of sold pigs. Questionnaire data were entered into a relational database software for analysis.

Serological Data

A total of 649 blood samples were collected from 175 pig farms in six districts of West Java and Banten, including Tangerang ($n = 22$), Tangerang City ($n = 6$), Bogor ($n = 30$), Bekasi ($n = 4$), Karawang ($n = 3$), and Kuningan ($n = 110$). The locations of the farms sampled within each of the six districts are shown in **Figure 2**.

The SIV serology status for each sampled pig was assessed using the ELISA-test for detection of influenza A nucleoprotein (NP)-specific antibodies using a commercial kit (IDEXX® influenza A Test Kit, Maine, USA). The presence or the absence of antibody to influenza A was determined using the sample to negative (S/N) ratio. According to the manufacturer's instructions, samples were identified as positive if the value of S/N was <0.5 and negative if S/N was ≥0.5. According to a previous report (29), the diagnostic sensitivity of the IDEXX influenza A is 86% (95% CI, 76–90%), and the diagnostic specificity is 79% (95% CI, 63–90%).

Statistical Analyses

We report both the apparent and the true herd-level prevalence of SIV seropositivity using the IDEXX ELISA. The apparent herd-level prevalence (AP) of SIV seropositivity was defined as the number of IDEXX ELISA-positive pigs per herd divided by the total number of pigs tested. True herd-level prevalence (TP) estimates take into account the imperfect diagnostic sensitivity (Se) and specificity (Sp) of the IDEXX ELISA using the approach (30) and modified for the extreme (i.e., low or high) prevalence situation using Bayesian methods (31). If x equals the number of pigs testing positive using a diagnostic-test of sensitivity Se and specificity Sp and n equals the number of pigs tested, the distribution of the number of test-positive pigs equals:

$$x|(TP, Se, Sp) \sim binomial(n,\ AP)$$
$$where AP = TP \ast Se + (1 - TP) \ast (1 - Sp)$$

To estimate the true prevalence of SIV seropositivity in each herd, beta prior distributions for Se and Sp were used. For the IDEXX ELISA, we assumed that the mode of the diagnostic sensitivity was 0.86 and that we were 95% confident that the diagnostic sensitivity was >0.76 (29). Similarly, we assumed that the mode of specificity of the IDEXX ELISA was 0.79 and that we were 95% confident that diagnostic specificity was >0.63 (29).

Markov chain Monte Carlo (MCMC) methods were used to derive posterior estimates of the within-herd TP of SIV exposure using JAGS (32). Using JAGS, the MCMC sampler was run for 100,000 iterations and the first 5,000 "burn in" samples discarded. The posterior distribution of TP was obtained by running sufficient iterations to ensure that the Monte Carlo standard error of the posterior means was at least one order of magnitude smaller than their posterior standard deviation (33). Herds were classified as SIV-positive if the within-herd TP of SIV exposure was >0 and SIV-negative if otherwise.

The association between general herd information characteristics, health management characteristics, and sources of pigs and herd-level SIV seropositivity status (defined on the basis of the true herd-level prevalence of SIV seropositivity, described above) was quantified using binary logistic regression (34). Putative risk factors associated with the outcome of interest at a significance level of $p \leq 0.25$ were selected for multivariable binary logistic regression modeling.

Pairs of putative explanatory variables that were associated with herd-level SIV status at $p \leq 0.05$ were checked for multicolinearity using chi-square-test for categorical variables. In the presence of statistically significant collinearity ($p \leq 0.05$), the variable considered to be the more biologically plausible risk factor for SIV was retained for multivariable logistic regression analysis.

A backward elimination process was used to select explanatory variables associated with herd SIV status. All putative explanatory variables that were associated with the outcome variable were entered into the model. Explanatory variables that were not significantly associated with herd SIV-seropositivity status were removed from the model one at a time, beginning with the least significant, until the estimated regression coefficients for all variables retained were significant at an α level of <0.05.

The final model's goodness-of-fit was evaluated using the Hosmer–Lemeshow-test, and the ability of the model to discriminate between SIV-seropositive and SIV-seronegative herds was assessed by constructing a receiver operating characteristic (ROC) curve. The area under the ROC curve, which ranges from zero to one, provided a measure of the model's ability to discriminate SIV-seropositive and SIV-seronegative herds. The greater the area under the ROC curve, the greater the model's discriminatory power (34).

RESULTS

A total of 175 farms were included in this study, with 147 of 175 (84%) of farms in West Java and 28 of 175 (16%) in Banten. The average number of pigs per farm in both provinces was 67.5 (median = 38, Q1 = 20, Q3 = 78.5), with most herd managers describing their enterprise type as non-commercial (155 of 175, 89%). In 170 of 175 (97%) farms, pigs were kept inside cages all day, while in the remainder of the herds, the pigs were kept in cages but could still have contact with other animals (e.g., birds, cats, or dogs). Most herd managers kept their sows for <2 years (138 of 175, 79%), and most herd managers kept animals such as dogs, cats, free-range chickens, and birds on farm (104 of 175,

TABLE 1 | Herd-level risk factors H1N1 swine influenza seropositivity, West Java and Banten provinces, Indonesia, 2016–2017, from multivariable logistic regression model.

Variable	OR (95% CI)	*p*-value
Presence of other animal species on farm		
Yes	2.5 (1.0–6.0)	0.03
No		
Length of time sows were kept on farm		
Less than 2 years	5.9 (1.8–20)	<0.01
More than 2 years		
Distance to nearest poultry farm		
Less than 1 km	2.4 (1.0–5.7)	0.03
More than 1 km		
Replacement pigs purchased only from a collector		
Yes	11 (4.3–29)	<0.01
No		

Cox and Snell, R^2 (p = 0.22); Hosmer–Lemeshow-test (p = 0.99).

60%). Seventy-one of 175 herd managers (41%) kept only pigs on farm. Ninety-one of 175 farms (52%) were located within the 1-km radius of commercial poultry farms, and 24% (42 of 175) of herd managers bought replacement pigs only from collectors, while the remaining 76% (133 of 175) bought replacement pigs from both other farmers and collectors.

In total, 649 serum samples were collected from 175 farms and tested for SIV H1N1, with 157 samples returning a positive result. The true herd-level prevalence of SIV seropositivity was 26 (95% CI, 20–33) herds per 100 herds at risk. SIV-seropositive farms were identified in all four districts (Bogor, Bekasi, Karawang, and Kuningan) of West Java and both two districts (Tangerang City and Tangerang) of Banten. Maps showing the location of SIV-seropositive and SIV-seronegative herds are shown in **Figures 2A,B**, respectively.

Our univariate analyses were carried out on 29 putative explanatory variables, with 16 of them associated with herd-level SIV seropositivity status at $p < 0.25$ (**Supplementary Table 1**). For multivariable analysis, four risk factors increased the risk of a farm to being SIV-seropositive: keeping animals apart from pigs on farm, keeping sows for <2 years, being <1 km away from a poultry farm, and purchasing pigs only through pig collectors (**Table 1**).

Our model provided an acceptable ability to discriminate between SIV-seropositive and SIV-seronegative herds, with the area under the ROC curve equal to 0.78. The model's accuracy was moderate to good (accuracy = 0.80; 95% CI, 0.73–0.85). While the model's sensitivity was low (0.36; 95% CI, 0.23–0.52), its specificity was good (0.95; 95% CI, 0.89–0.98).

DISCUSSION

One in four of the herds included in this study was SIV-seropositive, and SIV-seronegative herds were identified in all the six districts included in the study area. Our results show that the prevalence of SIV exposure in swine herds in this part of Indonesia is relatively high and that the SIV-seropositive herds in Java were geographically dispersed.

The strength of the association between each of the explanatory variables and herd SIV seropositivity status was similar in both the univariable and the multivariable analyses, which implies that none of the explanatory variables included in the multivariable analysis was an important confounder. Our finding that the odds of a herd being SIV-seropositive increased if other animal species (such as cats, dogs, and/or poultry) were kept on farm is in broad agreement with those of other studies. A cross-sectional study in Malaysia in 2005 (19) found that the presence of pets on farm (e.g., cats) was associated with an increased risk of H1N1 and H3N2 infection in pigs. Other studies have shown that the presence of poultry on pig farms was associated with an increased risk of swine being seropositive for SIV (17, 25). Pigs are susceptible to influenza virus infection from poultry and other mammals. For this reason, introducing and keeping other animals (e.g., dogs, cats, and poultry) is not recommended.

Our study showed that the risk of SIV seropositivity was increased on those farms where breeding sows were kept for <2 years. Swine farmers in this area of Indonesia did not routinely practice an "all in, all out" farm management system, which means that there is a relatively constant turnover of breeding sows entering and exiting a farm enterprise at any point in time. A management system whereby sows are kept for a relatively short period of time (i.e., 2 years or less) means that the herd replacement rate is relatively high, with frequent introductions of susceptible animals (either homebred gilts or purchased sows) into the herd population. If replacement sows are sourced from outside the farm, this process carries with it an increased risk of introduction of SIV into a herd (10). The findings reported here are in broad agreement with those of previous reports (17, 35), indicating that absence of an "all in, all out" management system and increased herd replacement rate were associated with an increased risk of SIV seropositivity in intensively managed swine herds in France and Spain.

If a farm was located within 1 km of a commercial poultry farm, the odds of the herd being SIV-seropositive was increased. The districts that were included in this study were in an area of Java where the density of commercial poultry farms is relatively high and where avian influenza H5N1 is endemic (36), which implies that swine farms in the same area are likely to be continuously exposed to avian influenza virus. We used ELISA to detect influenza A nucleoprotein antibodies, and it is possible that seropositivity in individual pigs could have been due to a cross-reaction between antibodies induced by influenza A subtype viruses from pigs (swine influenza) and those from poultry (avian influenza). In addition, SIVs are known to contain combinations of genes originating from humans and poultry (37), and some avian influenza viruses (non-human type has) can transmit directly and even continuously circulate in pigs (6). It is known that HPAI H5N8 virus particles can be detected in air sampled between 50 and 110 m from infected poultry farms (38), and influenza A viruses have been found in air samples between 1.5 and 2.1 km from poultry in Southern Minnesota and Northern Iowa (39). In Canada, it was found that pigs could be infected with avian H4N6 viruses [70]. Collectively, these findings support the hypothesis that avian influenza viruses can cross species and cause influenza infections in swine.

Purchasing replacement pigs only from pig collectors/traders was associated with an increased odd of SIV-seropositivity, consistent with the findings of a previous study that showed that this practice increased the risk of swine influenza H1N1 and H3N2 infection (19). In this area of Java, swine collectors source pigs for sale from numerous sources with varying levels of biosecurity, providing a biologically plausible explanation for our findings. Raising industry awareness of the role that collectors play as facilitators for pathogen transmission is important, with perhaps gains to be made by applying tighter controls on pig collectors who purchase pigs from farms located in poultry-dense areas.

With an area under the curve value of 0.78, we conclude that our final logistic regression model had moderate to good ability to discriminate between SIV-seropositive and SIV-seronegative herds (34). Our model was highly specific but had relatively poor sensitivity. This means that, when the model predicted that a herd was going to be SIV-seropositive, on 95% of occasions this prediction was correct. In contrast, there was a substantial proportion of herds (0.64; 95% CI = 0.56–0.70) that were truly SIV-seropositive that were not detected as such using the explanatory variables included in the final model (**Table 1**). These findings show that, while this study has been useful for identifying (or at least confirming) herd-level risk factors for SIV seropositivity, other risk factors remain. Detailed interviews with herd managers that had SIV-seropositive herds but were in the reference group for each of the risk factors listed in **Table 1** would be the first step toward identifying additional herd-level SIV seropositivity risk factors.

CONCLUSIONS

Our results show that the prevalence of SIV exposure in swine herds in this part of Indonesia is relatively high and that SIV-seropositive herds in Java were geographically dispersed. The presence of other animal species on farm, herds with a relatively high replacement rate, herds that were located in close proximity to poultry farms, and the routine practice of purchasing pigs only from a collector were all associated with an increased risk of the herd being SIV-seropositive.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to Directorate General Livestock and Animal Health Services (DGLAHS), Ministry of Agriculture (MOA), Jakarta, Indonesia.

ETHICS STATEMENT

Ethical approval was not required for this study according to national/local legislation because this was a retrospective study that evaluated national pig disease surveillance data (data from February 2016 to Novermber 2017) from Disease Investigation Center (DIC) Subang within the Directorate General of Animal Health and Directorate General of Livestock and Animal Health Services of the Ministry of Agriculture, Indonesia. No research on animals was undertaken, other than analysis of existing surveillance data.

AUTHOR CONTRIBUTIONS

VP and N: study design and concept. FZ, LS, and N: surveillance design and concept. FZ and TM: data management and lab testing. N, VP, MS, and CP: data analyses. N, VP, and FZ: drafting the manuscript. All authors: reviewed and finalized the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2020.544279/full#supplementary-material

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Household Macronutrient Prices and Livestock Health in Western Kenya

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Understanding food insecurity issues is in part contingent on understanding food consumption and its costs. We develop estimates of protein, lipid, and carbohydrate macronutrient consumption from household food consumption in western Kenya. We then calculate the shadow price per gram of macronutrient consumption as a share-weighted expense-consumption ratio. Using household bovine, goat, and sheep livestock health observations linked to each household, we analyze the association between livestock illness and macronutrient prices. We find that on average carbohydrates have a 75% budget share, with protein at 14% and lipids at 11%. Average macronutrient shadow prices are 0.0936 Ksh/g for carbohydrates, 0.4373 Ksh/g for protein, and 0.5938 Ksh/g for lipids. Average village-level livestock illness occurrences have significant effects on macronutrient shadow prices. Increasing average bovine illness at the village level by one additional case results in a marginal increase of the shadow prices of protein, lipids, and carbohydrates by 0.11, 0.12, and 0.03 (Ksh/g), respectively. Associated marginal impacts of sheep illness occurrence on protein, lipid, and carbohydrate shadow prices (Ksh/g) are 0.1405, 0.182, and 0.0455, respectively. This exploratory analysis provides empirical evidence that livestock illness is associated with increased macronutrient shadow prices, and hence the costs of available energy consumption. These results help guide policy instruments focused on market forces of nutrient consumption and its relationship with livestock health in undernourished areas with smallholder farming systems.

Keywords: nutrient consumption, production, development, livestock health, policy, nutrient costs

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INTRODUCTION

Sub-Saharan Africa has the lowest per person per day energy availability ranking worldwide (1). Availability, access, and utilization commonly define the pillars of food security (2). Food insecure households experience a failure of these pillars and consume an insufficient amount of nutrients. Negative health effects associated with malnourishment result in a failure to meet both cognitive and physical growth potential, which is linked to reductions in educational attainment and future earnings (3). The socio-economic impacts of food insecurity and its associated health effects consequently create an indirect effect of intergenerational poverty transmission (4). Increasing energy availability helps to provide opportunity for sufficient nutrient consumption, ultimately promoting health and welfare in underdeveloped areas.

Livestock represent a critical component in smallholder farming systems in underdeveloped areas (5). The agricultural household characterizes this smallholder farming system with production allocated toward subsistence needs and local market supply. The consumption of crops and animal sourced foods depends on the productivity of livestock within these systems. Livestock health directly affects productivity in terms of draft capability and meat production, which in turn affects nutrients available for consumption. Energy availability, and thus nutrient consumption, is partially dependent on the efficiency of livestock meat and crop production. Agricultural households with healthy livestock use feedstuff more efficiently for meat production and also use less human labor to augment unhealthy livestock crop production. Healthy livestock promote increased energy availability for the agricultural household and for local markets they supply, and also allow household members to allocate time toward economic activities other than crop production.

Nutrient consumption flows and the cost of nutrients provide important information on availability, access, and utilization of nutrients. The objective of this paper is to provide an exploratory analysis of rural western Kenya household macronutrient consumption and the association between livestock health and macronutrient prices, and consequently the association with costs of macronutrient consumption. Using household food consumption and livestock health observations, we accomplish this object by firstly converting food consumption into macronutrient consumption, and then secondly calculate per-gram macronutrient shadow prices for providing a measurement of macronutrient consumption costs, and lastly we specify an additive model relating livestock health to macronutrient consumption costs for evaluating their statistical association. The associated marginal effects of variation in livestock health on the variation of macronutrient consumption costs is evaluated through the additive model in a descriptive environment. Our findings contribute to current human health and development literature by providing quantitative measurements of macronutrient consumption costs and price impacts associated with variation in livestock health. This information benefits the construction of food consumption interventions particularly and nutrition policy in general in malnourished areas with representative smallholder farming systems.

DATA AND METHODS

The ongoing population-based animal syndromic surveillance (PBASS) socioeconomic system provides the data used for this study. This system enables health and economic analysis (6) through the collection of individual-level data from villages located in the rural western Kenya region. Data informing this study spans from February 2013 to June 2016 and consists of observations on household-level characteristics, food consumption, and expense, as well as livestock symptom presentation. Data collection occurs on a monthly basis through interviews gathering representative information on average food consumption and expense based on a 7-day recall, and observed livestock symptoms since last visit informed by both the household and veterinary professionals who visit the households. See (6) for research protocols and data collection details. We focus on bovine, sheep, and goats. While we recognize that these livestock species are not the only livestock used by households in this region, they are the livestock for which symptomatic health observations are available and linked directly to each household and its consumption patterns. We observe 588 unique livestock-owning households with ∼14 observations each over the sample period.

The United States Department of Agriculture (USDA) Food Composition Databases are used to convert food consumption into macronutrient consumption (1). Using macronutrient composition data for all food items consumed in our sample, we estimate household macronutrient intake as

$$N_h = \sum_{l}^{L} \sum_{j}^{J} \gamma_l F_j$$

where N represents total macronutrient consumption in grams for household h, γ represents the conversion factor for macronutrient l as the collection of protein, lipid, and carbohydrate, and F represents food consumption for food item j. The estimator for consumption in grams of individual macronutrients $N_{l,h}$ is characterized by removing the summation over L in the calculation of total macronutrient consumption above, providing $N_{l,h} = \sum_j^J \gamma_l F_j$.

The conversion factor γ for each macronutrient is provided by the USDA Food Composition Database in terms of macronutrient quantities per serving size of food item j. Food consumption F is converted to a measurement of total servings consumed, where the conversion factor is used to compute total macronutrient consumption for that particular food item.

The associated costs of macronutrient consumption are evaluated through the estimation of shadow prices, which reveal market information for goods whose prices are not directly observable. Each shadow price is estimated as a share-weighted expense-consumption ratio

$$P_{l,h} = \theta_{l,h} \left(\frac{E_h}{N_{l,h}} \right)$$

where P represents the per-gram shadow price household h pays to consume macronutrient l, θ represents the household's consumption share for each macronutrient, and E represents household food expense, which is defined as the cost a household pays for purchasing food items in a market environment. It is important to note that due to the nature of farming systems in this area, a proportion of total food items consumed observed in the data can come from home production of that item. An example is production of cow milk by a household cow with milk consumed by the household, where a proportion of total cow milk consumed is accounted for by their cow's milk production. However, this information is accounted for when estimating shadow prices of the macronutrients derived from the household's home-produced food item. To extend the previous example the shadow prices of macronutrients derived from home-produced cow milk reflect information on the cost of macronutrient consumption for that household producing some of its own food items. Compared to a household that does not produce cow milk, the household that does produce it realizes lower shadow prices for macronutrients derived from its consumption as its expense for that consumption is less. The cow milk example extends directly to all food items produced at home. We assume that a household is rational in their decision to produce a food item at home for a proportion of their total consumption of that food item, where the associated costs of producing that item are lower than purchasing that item in a market environment. The nature of food items is only important insofar as estimating macronutrient consumption. Discrimination between food items consumed takes place through varying consumption levels of macronutrients that make up these food items.

The statistical relationship between household macronutrient consumption cost and livestock health is explored in an additive regression framework. Additive, or linear model specification in general, evaluates systematic variation between a response variable and one or more independent variables related to the response variable (7). Evaluating how variables vary together allows for analysis of a statistical relationship between them. Livestock illness directly affects livestock production, which directly affects energy availability through supply in a subsistence and local market environment. We avoid placing constraints on the analysis by not specifying probability distributions or prior beliefs in the data generating process as called for in Bayesian environments (8), nor do we explore more elaborate functional forms due to risk of misspecification (9). Generally speaking, a linear model can be interpreted as a first order approximation to any functional form. Our analysis is an initial exploratory evaluation of estimating the statistical association between livestock health and the cost of macronutrient consumption.

Market forces influence household consumption patterns, which are accounted for by realized budget shares of consumption. Allocation of constrained resources to food items take into account the opportunity cost of consumption for competing goods. Consumption pattern decisions become a function of cost, income, and evaluation of welfare derived from consumption of competing goods. The effect of competing goods is known by the household when making consumption decisions, but is unobserved in available data (10). The stochastic error term in statistical models evaluating consumption decisions accounts for this unobserved effect.

We extend measurement of consumption patterns by estimating macronutrient shadow prices as a deterministic function of food consumption budget shares, which takes into account expense and implicitly places a lower bound on household income. Relating systematic variation in livestock illness to costs of macronutrient consumption takes place through livestock production. Existing literature explores the importance of livestock health in production by evaluating optimal control programs for decreasing mortality using dynamic programming methods (11), and through cost-benefit analysis showing high return on investment for animal health programs increasing production efficiency by decreasing the impacts of disease (12). Aside from the significance of livestock health in production, existing literature also explores the importance of livestock health in human welfare. There exists positive effects of increased livestock health on access to animal sourced foods and income generation for greater purchasing power in livestock-owning households (6). While livestock production is in part constrained by disease (13), and thus health, its contribution to income is significant in rural Sub-Saharan African households, which allows further access to animal sourced foods through purchasing power (14). Evaluating the systematic variation between macronutrient shadow prices, in which consumption patterns are subsumed, and livestock health through statistical association is supported by previous research evaluating links between livestock health, production, and human welfare through consumption and income.

While production methods are important in evaluating production outcomes, this study is interested in livestock health outcomes and its relationship with macronutrient shadow prices of household food consumption. To this end, livestock production methods and constraints are subsumed in livestock health outcomes. An example of this includes availability of feed and water. Inadequate availability or access to these production factors leads to malnourishment, poor production, and illness, with the latter of these outcomes observed through data.

Livestock health observations are used to characterize average livestock illness occurrence at village levels. The representative aggregate measure of livestock illness occurrence is used as an instrumental variable for determining household-level livestock illness occurrence due to a potentially endogenous effect between the household's food consumption expense and their production of animal sourced foods and crops. The presence of endogeneity is evidenced in literature examining household livestock production for subsistence and income generation in underdeveloped areas (6, 14). As food consumption expense is determined in part by household agricultural production, which is in part determined by livestock production and is influenced by livestock health, there exists simultaneity between food consumption expense and livestock illness at the household level. The simultaneous relationship leads to endogeneity problems in parameter estimation, resulting in estimation bias from error term correlation with included regressors (9). We remove simultaneity at the household level by smoothing livestock illness across all households and aggregate it to a representative figure at the village level, where any one household does not influence measurements at this level. This is accomplished by using average livestock illness occurrence for each village. This transformation still relates livestock health to cost of macronutrient consumption at the household level because of the homogeneity of household livestock production and livestock illness occurrence within villages, and lack of market mobility across villages.

Ordinary least squares error term assumptions of having an expected value of zero and being uncorrelated with included regressors are established through the use of average village livestock illness as an instrumental variable, which permits the evaluation of a statistical association between cost of macronutrient consumption and livestock illness. Because the number of household members explains consumption expense and must be controlled for due to its availability (7), it is also included in the additive model. The model relating livestock illness to cost of macronutrient consumption is specified as

$$P_{l,h} = \alpha_l + \beta_1 I_{v,m} + \beta_2 THM_h + \varepsilon_h$$

Let I represent average livestock illness occurrence for village v in month m, THM represent total household members for household h, and ε represent a random component explaining variation in the macronutrient's shadow price not explained by the included variables I and THM. The estimable parameters are α, β_1, and β_2 with the parameter of interest for livestock health effects being β_1. Given the panel data structure of sample data, inference on estimated parameters is conducted using a Heteroskedastic and Autocorrelation Consistent covariance matrix (15).

RESULTS AND DISCUSSION

Carbohydrates account for the largest proportion of consumed macronutrients with a share of ∼0.75 on average, as displayed in **Table 1**. **Figure 1** displays macronutrient consumption share trends over sample time. Noticeable in **Figure 1** is a subtle substitution effect between consumption of carbohydrates and consumption of protein and lipids. The substitution effects are more pronounced during the time frames July 2013–September 2013 and January 2016 - March 2016. On average, protein's consumption share is slightly higher at ∼0.14 than lipids' consumption share at ∼0.11. Our estimates of carbohydrate and protein proportions consumed agree with the range of macronutrient proportions found among adults across three ethnic groups in rural Kenya during a recent study (16). However, our estimate of the proportion of lipids consumed falls below their range of 14.5–30.2% mean estimates across ethnic groups. Differences in diets across ethnic groups contributes to the wide range of macronutrient proportions consumed, with access and availability of nutrients being an important factor.

Access to and consumption of carbohydrate rich foods is greater than that of consuming food items with a greater nutrient makeup of protein and lipids. The resulting macronutrient consumption shares for carbohydrates and protein are inline with the World Health Organization (WHO) and the Food and Agricultural Organization's (FAO) recommended macronutrient intake proportions for a balanced diet. The recommended range of total carbohydrate consumption is 0.55–0.75, with a range for protein of 0.10–0.15, and a range for total fats of 0.15–0.3. From the resulting macronutrient proportions it is estimated that on average, an upper bound of 25.5% of macronutrients consumed are from animal sourced foods. Using ranged macronutrient proportions to describe a balanced diet, this area of study sees proportions of carbohydrate and protein consumption at and toward the recommended upper range on average, respectively, with proportions of lipid consumption below the recommended lower range on average. WHO and FAO recommended dietary proportions establish population nutrition goals for the prevention of chronic diseases related to dietary intake (17). Further evidence supports the significance of diet diversification in nutrient rich items for promoting health development outcomes (18). However, it is important to note that while macronutrient intake proportions may fall inline with recommended proportions, with the exception of lipids, the total quantities of nutrients consumed are inadequate in promoting nourishment, as evidenced by the region's lack of energy availability (1).

On average, real macronutrient shadow prices (Ksh/g) are estimated to be 0.094 for carbohydrates, 0.437 for protein, and 0.594 for lipids, as displayed in **Table 1**. **Figure 2** displays mean macronutrient shadow price variation over sample time. Carbohydrate shadow prices are more stable across sample time than the shadow prices for protein and lipids. The standard deviation for mean carbohydrate shadow prices is ∼0.15, which is compared to the standard deviations of mean protein and lipids shadow prices at ∼0.29 and 0.4, respectively. Evidence of shadow price stability across time is seen in **Figure 2** with carbohydrate shadow prices revealing a relatively flat trend, while shadow prices for protein and lipids experience larger fluctuations.

Stability of availability and access, made possible through lower household cost and cost variation, results in consumption dense in carbohydrate rich foods. Lower consumption shares of protein and lipids are reflected through increased household costs. Consumption of lipids is estimated to be the most costly, while also having the most instability due to its larger variation. Framing this information in terms of market effects leads to speculation that lower lipid consumption is

TABLE 1 | Variable summary statistics ($N = 1078$).

	Dietary proportion			Shadow price (Ksh/g)				
	Protein	**Lipids**	**Carbohydrates**	**Protein**	**Lipids**	**Carbohydrates**	**Household livestock illness average**	**Total household members**
Mean	0.1433	0.1116	0.7451	0.4374	0.5938	0.0936	1.1531	4.8692
Std	0.0338	0.0577	0.0736	0.2878	0.4020	0.1525	0.2412	2.3239
Min	0.0066	0.0293	0.0345	0.0095	0.0041	0.0012	0.0000	1.0000
Max	0.5321	0.9588	0.9046	2.8381	4.9541	3.2035	3.0000	17.0000

Nutrient shadow prices are computed as share-weighted consumption-expense ratios and provide nutrient consumption costs in terms of Ksh/g. Sample data spans February 2013–July 2016. Nutrient Shadow prices are deflated using the February 2013 Kenya CPI. Livestock illness village averages are computed for each time period and averaged over the sampling period, representing the average number of ill livestock per household across all villages.

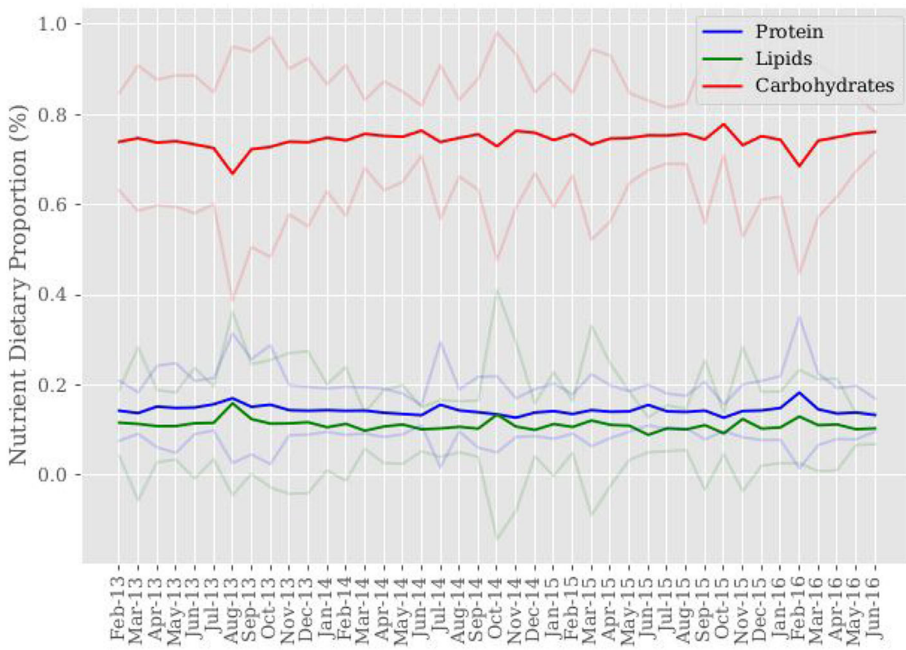

FIGURE 1 | Sample mean of nutrient dietary proportions. Nutrient dietary proportions are computed from nutrient-food item consumption conversions. Mean consumption proportion values are then computed for each month across sample time. 95% confidence intervals around mean consumption proportions are shown in color corresponding to each macronutrient.

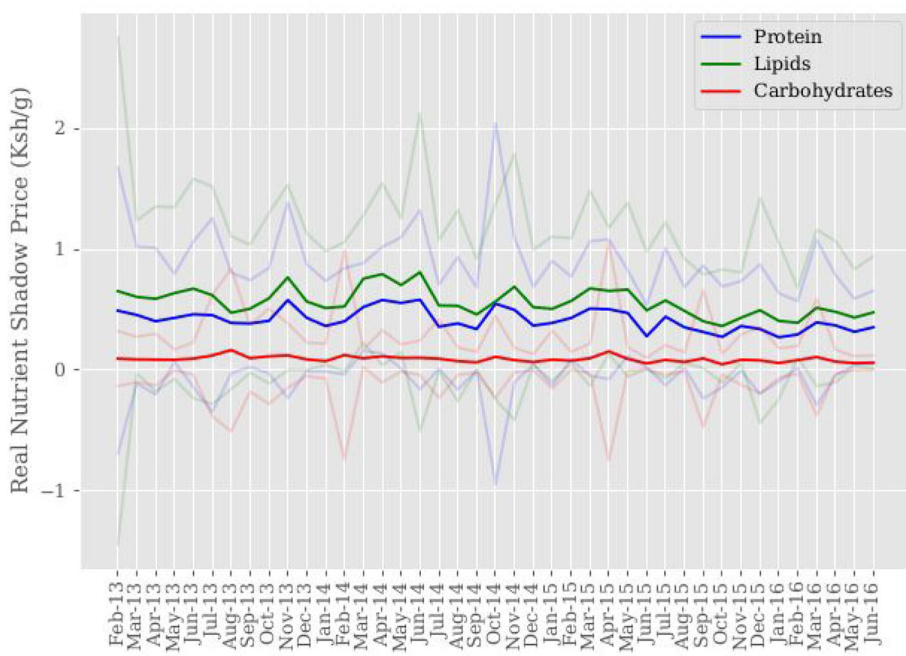

FIGURE 2 | Sample mean of nutrient shadow price (Ksh/g). Mean shadow prices for each nutrient are computed for each month across sample time. 95% confidence intervals around mean macronutrient shadow prices are shown in color corresponding to each macronutrient shadow price.

associated with increased cost of consumption as a result of lipid availability.

Utilization of protein and lipids rich food items is contingent on their availability and a household having access to them, in terms of being able to purchase or produce the food items. Animal sourced foods predominantly supply protein and lipids rich food items, which aid in cognitive and physical development (19). Understanding the determinants of availability and access to animal sourced foods then becomes a key issue in ensuring opportunities for both having balanced diets and a sufficient amount of nutrients for the energy needed to promote human health. Livestock health is one of the determinants of macronutrient availability through agricultural production, and information on a household's access to these nutrients is

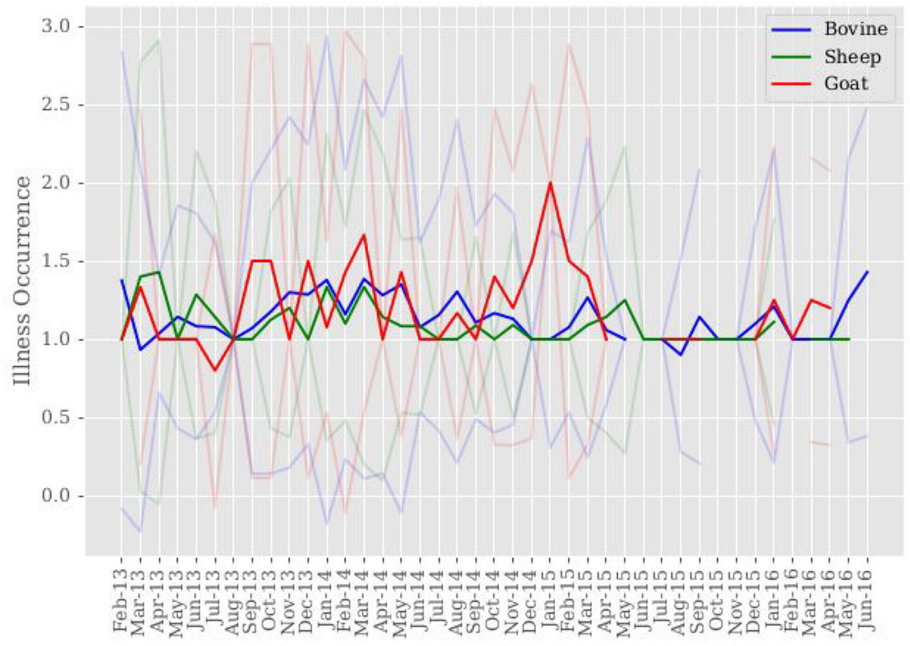

FIGURE 3 | Sample mean of livestock illness occurrence. Mean livestock illness occurrence is computed for each month across sample time. 95% confidence intervals around mean livestock illness occurrence are shown in color corresponding to each livestock species. Breaks in data correspond to having no household livestock observations. It is important to note this does not result in having no livestock illness occurrence, only that it is unobserved.

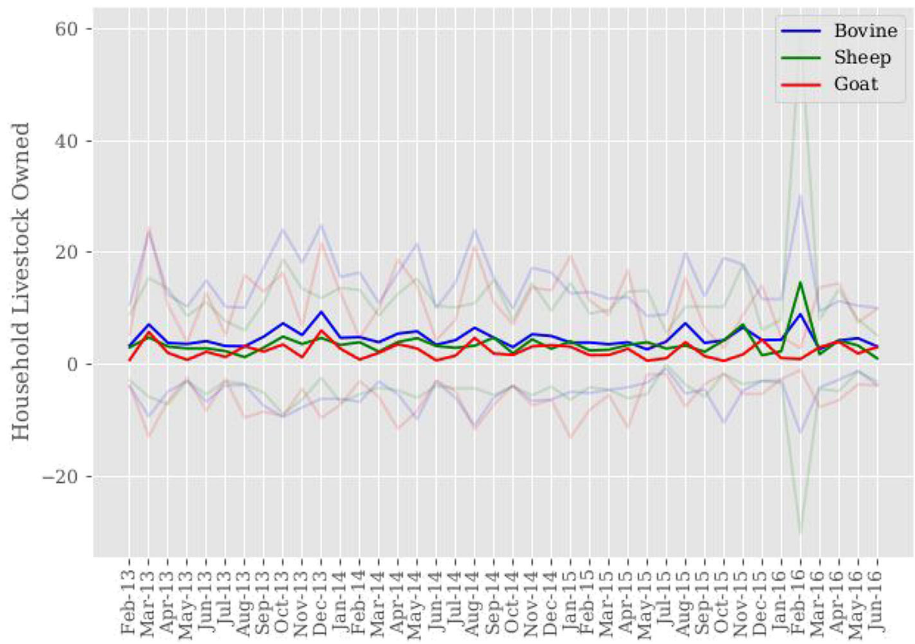

FIGURE 4 | Sample mean of household livestock ownership. Mean household livestock ownership is computed for each month across sample time. 95% confidence intervals around mean livestock ownership are shown in color corresponding to each livestock species.

evaluated through the marginal association between livestock health and consumption costs.

Per-month village-level livestock illness occurrence results in each household experiencing an approximate average of 1.15 illness occurrences in their own livestock each month. Livestock illness occurrences are defined as observed symptoms of reproductive, respiratory, digestive, urogenital, muscle, skin, and/or nerve disorders. The largest occurrence of observed bovine disorders are accounted for by digestive and skin disorders at rates of 0.67 and 0.32, respectively. Nerve and muscle disorders closely follow at rates of 0.27 and 0.24, respectively. Reproductive disorders are least observed at a rate of 0.005. The largest occurrence of observed goat disorders are accounted for by digestive and reproductive disorders at rates of 0.57 and 0.55, respectively. Respiratory disorder occurrence follows at a rate of 0.37. Nerve disorder is the least observed at a rate of 0.014. The largest occurrence of observed sheep disorders are accounted for by digestive and muscle disorders at rates of 0.77 and 0.29, respectively. Skin and respiratory disorders closely follow at rates of 0.14 and 0.13, respectively. Reproductive disorders are the least observed at a rate of 0.003. As a reference point, rates of general illness for bovine, goat and sheep are 0.55, 0.47, and 0.36, respectively. On average, households are made up of approximately five members.

Figure 3 presents average livestock illness occurrence across sample time aggregated to the sample level, not village level. Breaks in data correspond to having no household observations for that period when matching households across sample time on variables of interest when constructing the data set used for this study. We cannot say there is no livestock illness during these periods, only that it is unobserved. With the exception of February-April 2013, Bovine and sheep illness occurrences appear to be positively correlated across sample time. Visual inspection of **Figures 1–3** shows comparisons in trends of macronutrient proportions, shadow prices, and livestock illness occurrences. Notable periods include July-September 2013 and November-December 2014 where trends show slight increases in protein and lipid consumption with decreases in their shadow prices and livestock illness occurrence for bovine and sheep. It is speculated that the link between these trends is livestock health impact on food availability through production, which then impacts consumption decisions through cost.

Figure 4 presents average livestock ownership by species over sample time. Aggregated across households and sample time, households own on average 4.77 head of cattle, 3.49 sheep, and 2.51 goats. Livestock ownership appears stable across sample time, notwithstanding the increase in cattle and sheep ownership during the February 2016 time frame. It is speculated that household culling decisions give way to replacement decisions.

Regression Outcomes

Table 1 provides summary statistics of all model variables. **Tables 2–4** provide the associated marginal effects between bovine, sheep, and goat health and macronutrient shadow prices.

Average bovine illness occurrence is associated with significant marginal increases in shadow prices for carbohydrates, protein, and lipids at the 0.1 level. Unit increases in average bovine illness occurrence is associated with similar increases of ∼0.11 and ∼0.12 Ksh/g in the shadow prices of protein and lipids, respectively. The associated increase in the shadow price for carbohydrates is ∼0.03 Ksh/g when average bovine illness occurrence increases by unit amounts. Average sheep illness occurrence also shows significant associated marginal increases in shadow prices for all macronutrients. The shadow prices for protein and lipids again experience the largest associated increases by ∼0.14 and ∼0.18 Ksh/g when average sheep illness occurrence increases by unit amounts, with the shadow price for carbohydrates having an associated increase of ∼0.05 Ksh/g. Average goat illness occurrence does not show any significant associated marginal changes in macronutrient shadow prices.

Empirical elasticity distributions are calculated for bovine and sheep illness occurrences and reveal associated responses in macronutrient shadow prices to livestock illness events. A 50% empirical interval is used to convey information on the central mass of elasticity values falling between the 25th and 75th percentiles. A percentage change in bovine illness occurrence is associated with a change between 0.23% and 0.53% for the

TABLE 2 | Bovine health effects on nutrient shadow prices.

Dependent	Independent	Coefficient	Std errors	*t*-values	*Pr*(>|*t*|)	
Protein	Intercept	0.3197	0.0617	5.1796	0.0000	***
	Livestock illness avg	0.1113	0.0507	2.1934	0.0283	**
	Total HH members	−0.0044	0.0058	−0.7659	0.4438	
Lipids	Intercept	0.4172	0.0934	4.4678	0.0000	***
	Livestock illness avg	0.1210	0.0726	1.6658	0.0958	*
	Total HH members	0.0047	0.0071	0.6541	0.5131	
Carbohydrates	Intercept	0.0647	0.0162	3.9961	0.0001	***
	Livestock illness avg	0.0341	0.0142	2.4110	0.0159	**
	Total HH members	−0.0031	0.0024	−1.2785	0.2011	

*OLS specified regression results for bovine livestock health effects on costs of nutrient consumption at the household level. Covariance matrix is estimated using the (20) Heteroskedastic and Autocorrelation Consistent Covariance Estimator. {***, **, *} Significant at the {0.01, 0.05, 0.1} level. The adjusted R squared for protein, lipids, and carbohydrates models are 0.005, 0.002, and 0.005, respectively.*

TABLE 3 | Sheep health effects on nutrient shadow prices.

Dependent	Independent	Coefficient	Std errors	*t*-values	*Pr*(>|*t*|)	
Protein	Intercept	0.3072	0.0627	4.8987	0.0000	***
	Livestock illness avg	0.1405	0.0601	2.3364	0.0195	**
	Total HH members	−0.0047	0.0064	−0.7417	0.4582	
Lipids	Intercept	0.3334	0.0871	3.8271	0.0001	***
	Livestock illness avg	0.1820	0.0675	2.6980	0.0070	***
	Total HH members	0.0133	0.0081	1.6417	0.1006	
Carbohydrates	Intercept	0.0706	0.0182	3.8862	0.0001	***
	Livestock illness avg	0.0455	0.0263	1.7281	0.0840	*
	Total HH members	−0.0055	0.0045	−1.2164	0.2238	

*OLS specified regression results for bovine livestock health effects on costs of nutrient consumption at the household level. Covariance matrix is estimated using the (20) Heteroskedastic and Autocorrelation Consistent Covariance Estimator. {***, **, *} Significant at the {0.01, 0.05, 0.1} level. The adjusted R squared for protein, lipids, and carbohydrates models are 0.005, 0.002, and 0.005, respectively.*

TABLE 4 | Goat health effects on nutrient shadow prices.

Dependent	Independent	Coefficient	Std Errors	*t*-values	*Pr*(>|*t*|)	
Protein	Intercept	0.5620	0.1400	4.0134	0.0001	***
	Livestock illness avg	−0.0363	0.0605	−0.5994	0.5489	
	Total HH members	−0.0088	0.0152	−0.5810	0.5613	
Lipids	Intercept	0.7038	0.2005	3.5097	0.0004	***
	Livestock illness avg	−0.0495	0.1005	−0.4925	0.6223	
	Total HH members	−0.0009	0.0195	−0.0459	0.9634	
Carbohydrates	Intercept	0.1469	0.0506	2.9045	0.0037	***
	Livestock illness avg	−0.0373	0.0270	−1.3785	0.1681	
	Total HH members	0.0013	0.0074	0.1749	0.8612	

*OLS specified regression results for bovine livestock health effects on costs of nutrient consumption at the household level. Covariance matrix is estimated using the (20) Heteroskedastic and Autocorrelation Consistent Covariance Estimator. {***, **, *} Significant at the {0.01, 0.05, 0.1} level. The adjusted R squared for protein, lipids, and carbohydrates models are 0.005, 0.002, and 0.005, respectively.*

shadow price of protein, 0.19% and 0.44% for the shadow price of lipids, and 0.37% and 0.87% for the shadow price carbohydrates. A percentage change in sheep illness occurrence is associated with a change between 0.27% and 0.56% for the shadow price of protein, 0.26% and 0.54% for the shadow price of lipids, and 0.48% and 1.01% for the shadow price of carbohydrates.

The significant marginal increases associated with bovine and sheep illness occurrence, and macronutrient shadow prices reveal a positive relationship between macronutrient consumption cost and these species' illness occurrences. The adjusted R-squared values are reported in the notes section of each table. However, we are not interested in explaining variation in macronutrient shadow prices with the specified model, but rather are interested in evaluating an initial relationship between macronutrient shadow prices and livestock health through statistical association.

The significant association between bovine and sheep health on shadow prices is most notable in the protein and lipids macronutrients that animal sourced foods are rich in. While significant, the associated cost impact of carbohydrate consumption from bovine and sheep livestock health is approximately only a quarter of the associated increase experienced by protein and lipid consumption costs.

Evaluation of associated effects between livestock health and cost of macronutrient consumption provides insight on potential benefits derived from livestock health policy construction. Using the average of five household members, the associated shadow prices for protein, lipids, and carbohydrates during an average of one bovine illness occurrence for households are 0.4088, 0.5616, and 0.0833 Ksh/g, respectively. With no bovine illness occurrences for households, the associated shadow prices for protein, lipids, and carbohydrates are 0.2975, 0.4406, and 0.0492 Ksh/g, respectively. The associated percentage increases in protein, lipid, and carbohydrate shadow prices during bovine illness events are 37.4%, 27.5%, and 69.3%, respectively. Using the same measurement of an average of one sheep illness occurrence for households, associated shadow prices for macronutrients in the same order are 0.424, 0.5819, and 0.888 Ksh/g. With no sheep illness occurrences for households, associated macronutrient shadow prices are 0.2835, 0.3999, and 0.433 Ksh/g. The associated percentage increases in macronutrient shadow prices during sheep illness events are 49.6%, 45.5%, and 105.1% for protein, lipids, and carbohydrates, respectively.

Across all households and all villages average macronutrient consumption in grams for protein, lipids, and carbohydrates over the 7-day recall period is 1,810, 1,562, and 9,879, respectively. Costs savings of protein, lipids, and carbohydrate consumption associated with having an average of no bovine illness events are 201.42, 188.97, and 337.27 Ksh, respectively. Cost savings for macronutrient consumption in the same order associated with having an average of no sheep illness events are 254.3, 284.24, and 449.1 Ksh, respectively. Total cost savings associated with having no bovine illness events becomes 727.66 Ksh, with total cost savings associated with no sheep illness events at 987.64 Ksh. Associated cost savings are across weekly timeframes. As a reference point, for the year 2019 World Data reported an average monthly income in Kenya of 15,842.46 Ksh. Associated cost savings at the monthly level are ∼2,910.64 Ksh for households having no bovine illnesses on average, and ∼3,950.56 Ksh for households having no sheep illnesses on average.

We consider the most vulnerable households in our sample to be those with no supplemental off-farm income, whose total food expense is greater than the sample's 75th percentile, and whose total household members exceed the average of 5. The associated impact of livestock illness occurrences on macronutrient consumption cost for vulnerable households is greater than the associated impact on the sample's representative household. During bovine illness occurrences associated percentage increases in protein, lipid, and carbohydrate shadow prices are 44.6%, 31.5%, and 89.4%, respectively. Associated percentage increases in macronutrient shadow prices during sheep illness occurrences are 56.9%, 47.9%, and 150.1%, in the same respective order. Compared to a representative household, vulnerable households realize an associated percentage point increase of 7.2, 4, and 20.1 for macronutrient shadow prices during bovine illness occurrences, and 7.3, 2.4, and 45 during sheep illness occurrences.

Costs of policy implementation for increasing livestock health for purposes of increasing human welfare can be compared to the associated cost savings benefits for viability. It is important to note that these measurements only provide initial information on macronutrient cost savings associated with livestock health and should not be used in a definitive, predictive cost savings sense.

CONCLUSION

We have estimated macronutrient consumption and their shadow prices, which convey information on the costs households face in consumption decisions. We extend these cost estimates by evaluating variation between livestock health and costs of consumption through the systematic relationship between livestock health and production, and costs of macronutrient consumption and production. We have empirically shown a significant association between bovine and sheep health and the cost of macronutrient consumption. Proper nutrient availability, access, and utilization ensure nutritional requirements for healthy development are met. Increasing the costs of macronutrient consumption in already resource-stricken environments negatively impacts access to these nutrients, whereby decreasing the costs of macronutrient consumption facilitates increased consumption. The positive link between increased livestock health and production aids increases in nutrient availability, helping to decrease costs of macronutrient consumption and make access easier for households.

While our consumption proportion estimates agree with FAO and WHO balanced-diet ranges for carbohydrates and protein, and fall below the recommended range for total fats, current total nutrient consumption in our area of study is inadequate in providing levels of energy consistent with nourished environments. The promotion of health and future well-being is influenced by availability, access, and utilization of these macronutrients. Addressing initiatives seeking to understand macronutrient consumption and mechanisms that increase consumption can in part focus on areas associated with livestock health outcomes for developing areas representative of smallholder farming systems.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because data collection is ongoing as part of the Population Based Animal Syndromic Surveillance System and is property of agencies conducting the survey. Requests to access the datasets should be directed to alexander.kappes@wsu.edu.

AUTHOR CONTRIBUTIONS

AK and TM contributed equally in model design, testing, and writing. All authors contributed to the article and approved the submitted version.

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METHODS
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Tropical Livestock Units: Re-evaluating a Methodology

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The dynamic between humans, livestock, and wildlife is evolving owing to growth in populations, a finite global landmass, and shifting climatic conditions. This change comes with certain benefits in terms of food security, nutrition, and livelihoods as livestock populations increase, but is not without risk. The role of livestock in infectious disease emergence, environmental degradation, and the development of antimicrobial resistance is becoming more apparent. An understanding of these risks and development of mitigation tactics, especially in low- and middle-income countries where the pace of change is most rapid, is increasingly based on comprehensive models and tools built to map livestock populations at the global, regional or national level. Translation of model estimates into evidence is often underpinned by a quantification of livestock biomass to support policy development and implementation. This paper discusses the application of the Tropical Livestock Unit in the context of measuring biomass. It examines the established method of calculation, designating all cattle a standard weight of 175 kg, and compares it to two proposed alternatives. In doing so, the potential to refine estimates of biomass in low and middle-income countries is explored, though this concept could be extrapolated to higher income economies as well. Publicly available data from six countries in sub-Saharan Africa was utilized to demonstrate how breed liveweight, herd structures, and growth rates have the potential to dramatically alter the estimates of cattle biomass in each country. Establishing standardized data collection procedures to capture this information on a regular basis would grant a better understanding of the true nature of livestock populations, aid in the development of superior disease prevention and response measures, bolster food security initiatives through improving livestock production, and inform the intelligent management of shared ecosystems to improve conservation and biodiversity.

Keywords: tropical livestock unit, TLU, biomass, livestock, food security

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INTRODUCTION

Driven by growing prosperity and expansion of the world's population, expected to reach 9.7 billion by 2050, demand for animal-derived products is expected to rise considerably over the next century (1, 2). Concurrently, infectious disease emergence, climate change, and loss of biodiversity increasingly threaten food security, human health, and the global economy (3). With Africa expected to contribute 50% to global human population growth, the pace of change, and the escalation of these risks, are expected to be most rapid in low and middle-income countries (LMICs) (4, 5).

Livestock populations in LMICs (as defined by the World Bank) are already seeing a steady increase in numbers alongside population growth and wealth increase (6, 7). In Kenya for example, a country defined as lower-middle-income by the World Bank, cattle populations are projected to increase by 94% and poultry by 375% between 2015 and 2050 (7, 8). Initiatives to expand and intensify production systems as well as improve species production potential are underway in many LMICs (9, 10). Simultaneously, the risks inherent in the rapid transition and concentration of livestock systems are recognized, and attempts to more accurately map and manage populations have been made. Central to mapping efforts, the Gridded Livestock of the World database, initially published in 2007 and now in its third edition, has modeled livestock distribution and density around the world using data compiled through censuses and national statistics, cross-referenced with the Food and Agriculture Organization of the United Nation's FAOSTAT database (11). Researchers have also leveraged this data to inform mapping of global livestock biomass distributions (12–14). The distribution and density mapping efforts exemplify the increasing level of resolution that analytic methods are looking to capture, however that level of granularity is not mirrored in the estimation of biomass by tropical livestock units (TLU), which are foundational in much of the work done in LMICs.

Measuring 250 kg of liveweight, the TLU has been used as the reference point to factor livestock of different species by biomass in LMICs since at least the mid-20th century (15). In his 1982 manual, *Livestock Production Systems and Livestock Development in Tropical Africa*, Jahnke (15) discussed the convenience of being able to quantify a variety of forage-consuming domesticated animal species through the TLU as a means of informing rangeland carrying capacity and stocking rates. The camel, as the largest livestock species in tropical regions at that time, with an average liveweight of 250 kg, was defined as 1 TLU; further conversion factors were established for the remaining species. Cattle were assumed to have an average weight of 175 kg, equating to 0.7 TLU per head, with 0.1 TLU per head allocated for sheep and goats, 0.2 for pigs, 0.8 for horses, 0.7 for mules, 0.5 for asses, and 0.01 for chickens.

The same conversion factors as outlined in the mid-20th century are still in use to quantify the biomass of species today, however, weaknesses in this method of calculating and utilizing the TLU appear abundant. When considering a species, averaging the weight of animals regardless of breed, sex, or age fails to account for vast differences that could be observed when assessing population structures. Doing this precludes any possibility of monitoring change within a species population that may appear as a result of breed or nutritional improvement, or from negative factors such as disease, lack of access to adequate nutrition, or other climatic or environmental variables. In consideration of stocking densities—the original inspiration for developing the TLU—the importance of grasslands as a means of grazing livestock, sustaining wildlife, reducing soil erosion, and mitigating greenhouse gasses has grown increasingly important and it is evident that assessment of impacts must become more precise (16). Yet, all cattle, regardless of age, breed, sex, or agricultural purpose (e.g., meat vs. dairy) are presently still estimated to average 175 kg liveweight; all small ruminants are averaged at 25 kg per head, and all chickens averaged at 2.5 kg per bird. Additionally, this method of calculating biomass does not consider differences in feed conversions, growth rates, or production efficiency specific to different animals. Even in early mentions of the TLU and the animal unit or animal unit equivalent (similar biomass measurement tools used in the United States for informing stocking densities) it was acknowledged that an animal's metabolic weight, fertility rate, and the herd structure must be considered in the context of potential intake to generate the most accurate calculations (15, 17, 18). It would seem then to be completely erroneous, for example, to assume that 70 chickens would have the same value, nutritional needs or greenhouse gas emission potential as one cow.

Increasingly, however, livestock density patterns and biomass estimates using the TLU are being utilized to underpin evidence in research on a variety of factors: to identify at-risk populations in consideration of climate change and impacts on food security; to determine land carrying capacity; to examine stocking rates for the purpose of supporting proposals for livestock development projects; and as an indicator and predictor of wealth or diversification of income (14, 19–24). Livestock biomass has also been explored extensively in relation to greenhouse gas emissions (GHG) either directly from animals or as a result of their excrement or impact on soils (24, 25). Physical pressures on a landscape are mitigated by a variety of factors, however, it is evident that biomass, along with whether the animal is a ruminant or monogastric herbivore are key components, particularly in the production of methane (26, 27).

The availability of data on animal weights, breed characteristics, and population numbers is greater now than in the past through the work of research groups, breed societies, and aggregation by databases such as FAOSTAT and FAO Domestic Animal Diversity Information System (DAD-IS) (11, 28). In response to these factors, this paper explores alternative methods for estimating population biomass as a comparison to the traditional TLU estimation method, demonstrating the potential impact on total biomass estimates. An improved estimation of biomass has vital and far reaching applications in the monitoring of the health, nutrition, and environmental impacts of livestock production in LMICs and will be an important scale factor in the estimation of economic impact of disease through the Global Burden of Animal Diseases (GBADs) program (29).

METHODS

To explore how traditional biomass estimates differ when compared with estimated average cattle liveweight in each country, FAOSTAT and FAO DAD-IS databases for the years 2010–2020 were cross-referenced. Countries that were selected reported all four of the following data points in the same calendar year:

- Population head of cattle (DAD-IS; FAOSTAT);
- Carcass weight data (FAOSTAT);
- Head of cattle per breed (DAD-IS), totaling at least 91% of FAOSTAT population;
- Weight data for males and females of each breed (DAD-IS).

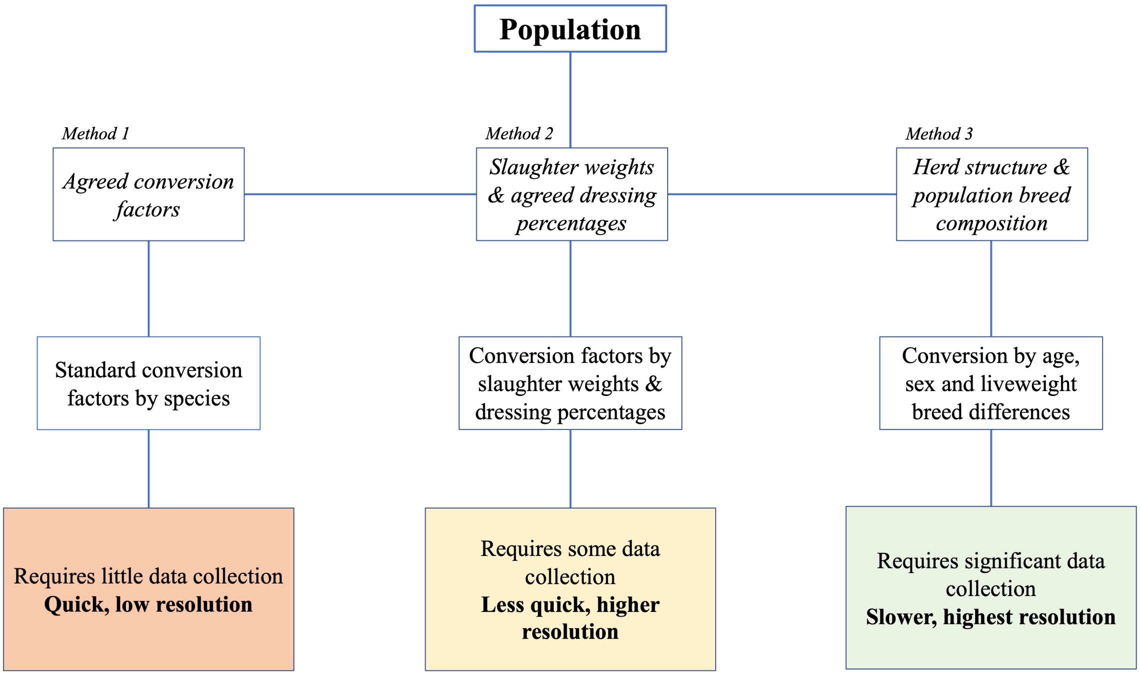

FIGURE 1 | Estimating tropical livestock units of a given [cattle] population requires an understanding of population biomass. Historically, herd biomass has been estimated by multiplying the population number by an average liveweight estimate of 175 kg (Method 1). We argue that while Method 1 may be expedient, it does not accurately represent population biomass. Therefore, we propose that an understanding of herd structure and breed composition, as well as an understanding of the age, sex, and breed liveweight differences is essential to a complete understanding of population biomass and conversion to an informed TLU calculation (Method 3). In the absence of data required to implement Method 3, an interim solution is use of slaughter weights and agreed dressing percentage to inform liveweight biomass estimation (Method 2).

FAOSTAT herd population estimates and DAD-IS population data were reviewed to verify they were within a 90% identical range. Only six sub-Saharan African countries matched the search criteria: Burundi (2013), Malawi (2013), Mali (2015), Mozambique (2018), Niger (2018), and Senegal (2019).

Using this data, three ways of calculating livestock biomass were compared (**Figure 1**):

1. Use of population estimates (DAD-IS) with standard weight-based TLU conversion values.
2. Use of population estimates with liveweight defined by dressed carcass weight at slaughter (FAOSTAT) and a standard dressing percentage.
3. Use of population estimates by breed and associated weight data (DAD-IS) with an assumed herd structure.

Method 1

As a baseline for comparison, average cattle liveweight (175 kg) was divided by 250 kg to convert to TLUs by the standard method and then multiplied by population (head) in each country (Equation 1). Cattle population was represented using DAD-IS estimates (>91% identical to FAOSTAT population estimates) to streamline further analysis comparisons between the methods.

$$TLUs = \left(\frac{175}{250}\right) \times population \quad (1)$$

Method 2

Using year-specific average dressed carcass weights obtained from FAOSTAT for each country, carcass weight was divided by standard-use cattle dressing percentage of 55% to find average liveweight (Equation 2). Average liveweight was then divided by 250 for conversion to TLU.

$$Average\ liveweight = \frac{Dressed\ carcass\ weight}{Dressing\ percentage} \quad (2)$$

Method 3

The third method used breed population and weight data obtained from DAD-IS for each country. The cattle population of each country was compartmentalized by breed, such that for each breed, n_i represents the population of breed i within the country. Within each breed, the population was then further divided into calves, young stock, adult males, and adult females: the proportion of each being P_c, P_y, P_b, and P_f, respectively. The average liveweight for each age category (W_c, W_y, W_b, and W_f) was then weighted by proportion to calculate an average liveweight for the breed (W_i) (Equation 3).

$$W_i = P_c \cdot W_c + \frac{P_y\left(W_b + W_f\right)}{2} + P_b \cdot W_b + P_f \cdot W_f \quad (3)$$

To illustrate, a population structure of 20% calves, 25% young stock, 35% adult females and 20% adult males was assumed.

TABLE 1 | Herd biomass estimates derived from a standard average of 175 kg per head.

Country	Year	Head	Biomass by standard average (head × 175kg)	TLUs
Burundi	2013	690,000	120,750,000	483,000
Malawi	2013	1,241,749	217,306,075	869,224
Mali	2015	9,747,326	1,705,781,963	6,823,128
Mozambique	2018	2,007,936	351,388,800	1,405,555
Niger	2018	13,788,596	2,413,004,300	9,652,017
Senegal	2019	3,642,866	637,501,463	2,550,006

Calves were defined as birth to 6 months of age and were assigned an average weight of 50 kg; young stock were defined as 7–18 months of age and assumed to average 50% of adult weight with an even sex split. The contribution of each breed to biomass was then calculated as the product of W_i and n_i. Each breed biomass was then summed by country to estimate a total biomass in kilograms, which was converted to TLU as 1 TLU = 250 kg.

RESULTS

A review of the results shows that in all six of the countries, biomass estimates were considerably higher when alternative methods of calculation are applied. Results of the traditional method of calculating herd biomass by a standard average of 175 kg (section Method 1) are shown in **Table 1** alongside total estimated biomass for each country.

Data obtained from the FAOSTAT database for average dressed carcass weights by country in Method 2 illustrate that carcass weight was greater than Method 1 liveweight estimates (all cattle equal to 175 kg) in Burundi, Niger, and Senegal which reported average dressed carcass weights of 200, 278, and 188 kg, respectively. Conversion of all average carcass weights to liveweights using Method 2 found animals averaged between 224 and 505 kg liveweight (**Table 2**) which, when compared with Method 1 standard liveweight of 175 kg, yielded between 116 and 289% greater [total] biomass across the countries reviewed. This is illustrated in **Table 4** where biomass per country obtained through Method 1 is shown as a percent of biomass derived through Method 2.

Analysis of data obtained from DAD-IS found between 1 and 12 different breeds represented in each country with reported liveweights for adult females ranging from 230 to 800 kg and adult males ranging from 300 to 1100kg. Analysis of Method 3 illustrated that application of herd structure in the context of breed data yielded greater total biomass (**Table 3**) and larger average liveweights than Method 2 in all but one country (Niger) (**Table 4**). A comparison of results between Methods 1 and 2 found the standard method of calculation captured between 35 and 86% of total biomass compared to Method 2, and between 41 and 75% of total biomass compared to Method 3 (**Table 4**).

TABLE 2 | Total biomass derived through conversion of all average carcass weights to liveweights using a standard dressing percentage of 55%.

Country	Average carcass weight (kg)	Liveweight (kg)	Converted to TLU	Total national biomass (kg)	TLUs
Burundi	200	364	1.5	250,909,091	1,003,636
Malawi	112	204	0.8	252,865,251	1,011,461
Mali	123	224	0.9	2,179,856,430	8,719,426
Mozambique	162	295	1.2	591,428,422	2,365,714
Niger	278	505	2.0	6,969,508,524	27,878,034
Senegal	188	342	1.4	1,245,197,662	4,980,791

TABLE 3 | Biomass estimates derived through by compartmentalization of specific country breed and associated weight data into an assumed herd structure.

Country	Average Liveweight (kg)	Total biomass (kg)	Total TLUs
Burundi	430	296,866,750	1,187,467
Malawi	233	289,793,173	1,159,173
Mali	265	2,587,612,287	10,350,449
Mozambique	455	912,737,392	3,650,950
Niger	282	3,889,560,765	15,558,243
Senegal	365	1,328,395,973	5,313,584

TABLE 4 | Comparison of biomass estimation methodologies.

Country	Year	Average Animal Liveweight (kg)			Ratio of total biomass	
		Method			Method 1 as a % of Method 2	Method 1 as a % of Method 3
		1	2	3		
Burundi	2013	175	363.6	430.2	48%	41%
Malawi	2013	175	203.6	233.4	86%	75%
Mali	2015	175	223.6	265.5	78%	66%
Mozambique	2018	175	294.5	423.6	59%	38%
Niger	2018	175	505.5	282.1	35%	62%
Senegal	2019	175	341.8	364.7	51%	48%

DISCUSSION AND CONCLUSIONS

The intention of this paper was to fulfill two purposes. First, to ascertain whether deviations from an average cattle liveweight of 175 kg would yield significant changes in biomass estimates in sub-Saharan Africa, and second, to use publicly available datasets to generate estimates of average liveweight for comparison to the 175 kg benchmark. The investigation demonstrated that there is capacity to introduce a greater degree of fidelity into biomass estimates for livestock populations. The data extracted from the DAD-IS and FAOSTAT databases are suggestive of a trend toward under-estimation of cattle liveweight in the current biomass estimation methodology, in particular in the central and southern African countries examined here, and in those countries with a greater introduction of exotic genetics. Indeed, failure to update average liveweights when considering TLUs fails to recognize the significant efforts made by various groups to improve the genetics and nutritional input of livestock species in tropical regions, an agenda that is hailed ever more frequently at the policy table.

It is acknowledged that some limitations must be taken into consideration when appraising our analysis. First, Method 2 is based on the assumption that dressed carcass weights are directly representative of average liveweight in the population at large, and that all cattle produce a dressing percentage averaging 55%. These are clearly dubious assumptions to make, given that this sample is likely to include both emergency and regular slaughter animals, as well as recent imports through trade, and unlikely to include many calves. The choice to use an average cattle dressing percentage (also referred to as killing-out percentage) of 55% could further inhibit calculation of exact liveweight estimations. A dressing percentage is calculated as the proportion of animal mass that is considered fit for consumption. While studies have attempted to estimate dressing percentage in different breeds and environments, it is difficult to extrapolate across geographies when dressing percentage and the "dressing difference" (visceral fat, blood, and other parts that are generally not consumed by humans) can vary in both quantity and definition by breed and country (30, 31).

Secondly, the FAO collects and disseminates agricultural data from over 245 countries and territories, which includes estimated livestock populations and commodities production approximations (32). These data are compiled by FAOSTAT using reports provided by country governments. The FAOSTAT and DAD-IS databases were selected for use in this project because they harbor a vast amount of data presented in a standardized fashion. However, it is acknowledged that the sources of data vary in collection methodology depending on country of origin, and that where data is missing, FAOSTAT in particular applies extrapolation methods to fill gaps. This may also explain why a comparison of cattle population estimates from DAD-IS with FAOSTAT are not generally found to be identical. Indeed, only six sub-Saharan African countries had >90% identical population estimates when DAD-IS and FAOSTAT data were compared. This may be explained by a small percent of the cattle population in each country falling outside defined breed standards as reported by DAD-IS, but the authors were unable to find a published explanation for this discrepancy. A further limitation related to FAO database estimates surrounds quality of data reporting on carcass weights which are unlikely to be homogenous even within the example countries. It should be highlighted for instance that in our dataset, Niger has an abnormally high dressed carcass weight for 2018. This data was accessed by us in mid-February 2020 and found to be marked as "calculated data." Therefore, it may change in the database and thus nullify any calculations drawn from it if an error in the data is identified by the publisher.

In Method 3, we attempted to increase granularity by including breed specific data and average bodyweights for populations, combined with assumptions about population structure. In this example, a hypothetical herd structure was applied. The classifying of production systems in sub-Saharan Africa is a large task in itself, and herd structures comprise just one aspect of that (33). To the best of the authors' knowledge, no publicly available repository of data on herd structures within these regions is available at present to support the level of detail proposed here. Therefore, while the authors took advantage of DAD-IS breed data where possible (e.g., available weight data by sex), it was necessary to make use of some herd structure generalizations. This is a limitation of Method 3 which the authors fully acknowledge and propose could be explored in more depth with a sensitivity analysis if more comprehensive data were available. At present, however, given the acknowledged data gaps and a lack of confidence intervals around most of the data published by the FAO, a sensitivity analysis would yield no additional value. Further, the authors note that while the choice to use FAOSTAT and DAD-IS data was made in order to demonstrate facility of the methodologies using widely accepted data repositories, the methodologies discussed in this paper should be considered a demonstration of what could be possible given greater data confidence, rather than a concrete representation of current cattle biomass in the example countries. Thus, estimations of biomass should be re-assessed and may be adapted within these methods as more accurate and detailed population weight estimates and herd structures are made available. Nevertheless, it is believed a few additional corroborating variables introduced as a more structured national herd data collection protocol formulated and disseminated by the FAO could allow aspects of the sector, such as slaughter data, to increase the accuracy of biomass estimation.

Finally, it should be noted that while this paper explores cattle as the model population, the methodologies explored could be similarly applied to other livestock species including small ruminants, pigs, camels, equines, and poultry.

The impetus for considering livestock biomass in the early 20th century was to develop stocking rate estimates for rangeland systems in order to issue recommendations on how many animals could be sustainably grazed on a given area of land. The practice has since evolved in application to underpin critical indicators for food security, public health, and both local and regional economies. As humans and other terrestrial animals, both livestock, and wildlife, come into more frequent and closer contact with each other by nature of finite global landmass and a shared need for adequate nutrition, it has become ever more important that an understanding of physical biomass in a given space can be accurately measured. Given the analysis generated above, it is therefore appropriate to question whether studies that utilize the traditional TLU biomass estimates to support research should be called into question. A potential underestimation of the scale we have demonstrated casts doubt, for example, on whether GHG emissions estimates based on TLUs are accurate, or if measures of feed required to sustain a given population are sufficient. If biomass is miscalculated to the order of magnitude our analysis suggests, the bedrock on which many understandings, policies, and initiatives are built could be questioned. A more precise TLU could substantially enhance food security through more informed livestock production, enhance disease prevention and response capacity, and better equip decision makers in intelligent management of vital ecosystems for equity, sustainability, and biodiversity.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: FAOSTAT: http://www.fao.org/faostat/en/#data and DAD-IS: http://www.fao.org/dad-is/en/.

AUTHOR CONTRIBUTIONS

PR-O, JR, and WG conceived the study. PR-O was responsible for drafting the manuscript, designing the methodology, and undertaking the data analysis. JR oversaw the study design and analysis. WG contributed to methodology design and data analysis. All authors contributed to the article and approved the submitted version.

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Financial Impacts of Liver Fluke on Livestock Farms Under Climate Change–A Farm Level Assessment

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Liver fluke infection (fascioliasis) is a parasitic disease which affects the health and welfare of ruminants. It is a concern for the livestock industry and is considered as a growing threat to the industry because changing climatic conditions are projected to be more favorable to increased frequency and intensity of liver fluke outbreaks. Recent reports highlighted that the incidence and geographic range of liver fluke has increased in the UK over the last decade and estimated to increase the average risk of liver fluke in the UK due to increasing temperature and rainfall. This paper explores financial impacts of the disease with and without climate change effects on Scottish livestock farms using a farm-level economic model. The model is based on farming system analysis and uses linear programming technique to maximize farm net profit within farm resources. Farm level data from a sample of 160 Scottish livestock farms is used under a no disease baseline scenario and two disease scenarios (with and without climate change). These two disease scenarios are compared with the baseline scenario to estimate the financial impact of the disease at farm levels. The results suggest a 12% reduction in net profit on an average dairy farm compared to 6% reduction on an average beef farm under standard disease conditions. The losses increase by 2-fold on a dairy farm and 6-fold on a beef farm when climate change effects are included with disease conditions on farms. There is a large variability within farm groups with profitable farms incurring relatively lesser economic losses than non-profitable farms. There is a substantial increase in number of vulnerable farms both in dairy (+20%) and beef farms (+27%) under the disease alongside climate change conditions.

Keywords: climate change, liver fluke, livestock farms, farm level modeling, economic impact study

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INTRODUCTION

Liver fluke (fascioliasis) is a parasitic disease caused by *Fasciola hepatica* and is distributed globally (1). The disease is a concern for livestock industry both from an animal health perspective but also due to the economic consequences on production systems. The economic impact is caused by lower production due to reduced body weight, milk yield and fertility as well as health conditions such as diarrhea and mortality in cattle (2). It is estimated to cost the livestock sector around £2 billion per year globally (3, 4). Liver fluke is endemic in the United Kingdom costing the cattle industry between £13 and £40 million annually (5) and more recent estimate is £31 million per year.

Liver fluke has a complex lifecycle with definitive mammalian hosts (primarily cattle and sheep), a number of free-living stages in the environment, and an intermediate molluscan host *Galba truncatula* (a species of pond snail). The parasite's free-living stages thrive in warm and wet conditions which also promote the survival and reproduction of *G. truncatula*. Due to the influence of temperature and moisture on multiple stages of this lifecycle, changing climatic conditions influence the timing, intensity, and distribution of fascioliasis outbreaks. The dynamics of livestock parasites and hence the disease patterns are shifting under climate change with larger spread and more frequent outbreaks of disease (2, 6–9). For example, liver fluke outbreaks were historically restricted to the south west of the UK, but it is spreading to other regions especially north of the UK more recently (10, 11). The future climatic conditions are projected to increase liver fluke incidences on livestock farms in the UK (12). Predictions of long-term fluke risk indicate that future risk is greater than past risk across the UK, and some areas are set to experience unprecedented epidemics over the next 60 years (12). An ex-ante study, hence, to estimate economic losses from the disease at production level under future climate is essential to control and minimize the impacts of this disease. It can be used to highlight the importance of making long term decisions to control the disease and minimize such risks in advance. Several studies have suggested that different farms respond differently to changed farm conditions (such as policy changes or disease outbreaks) due to the variabilities present between them (13–17). It is hence essential to look at the impacts of the disease at farm level to determine where the impacts would be greater. This paper aimed to determine the disease impacts on farms taking account of farm variability. The variability was based on production systems (dairy and beef production systems) and on farm profitability. There are substantial differences in profitability between farms in Scotland where many farms rely heavily on farm support payments to stay profitable (18). This makes them vulnerable to any type of changes in support payment policies especially in recent times when the UK agricultural policies are undergoing some significant changes bringing in uncertainties associated with support payments in future (17, 19). This paper used farms' reliance on farm support payments to be an indicator of farm economic vulnerability and explored changes in the number of vulnerable farms under the disease scenarios. A dynamic optimizing farm level model, ScotFarm was implemented for this study which used farm net profit as a measure to determine the economic impact of the disease on dairy and beef farms. This paper contributes to improve our understanding on long term economic impacts of liver fluke disease on Scottish livestock farms with and without future climate change conditions at a farm level.

METHODOLOGY

ScotFarm Model

ScotFarm is a farm-level linear programming model that optimizes financial margins of a farm within its bio-physical constraints (20). This model has been used in a number of earlier studies (21–24). The model maximizes farm net profit which is the sum of gross revenues from all farm activities and farm support payments such as Basic Payments Scheme and Less Favorable Area Scheme (25, 26), minus fixed costs (FC). Farm net profit is measure that is used widely to measure farm's financial performance (18, 19, 27). The general mathematical formulation of maximizing farm net profit was as follows:

$$Max\ Z = \sum_i [grev_i]x_i + FS - FC \qquad \forall f$$

Subject to

$$\sum_i A_i x_i \leq b_f \ ; \ \ x_i \ \geq \ 0 \qquad \forall f$$

Where Z denotes maximized net profit of all activities from all the enterprises of a farm; *grev* represents gross revenue of an enterprise; index i denotes agricultural activities including livestock and crop while f denotes individual farms; $x_{,i}$ is the non-negative activity level in hectares or heads of farm f activity i; *FS* represents all support payment received by a farm; *FC* is total fixed costs; A is an input–output coefficient for activity x; and b denotes limited farm resources.

Gross revenue of an enterprise ($grev_i$) was estimated as follows:

$$grev_i = \sum p_{i,j} y_{i,j} - \ CR_i - \sum VC_i - \sum NC_i \quad \forall f$$

Where p denotes price of output j, y is the quantity of output *j per activity* $x_{,i}$; *CR* denotes the cost of replacement; *VC* represents variable costs (including labor, veterinary and AI costs) and *NC* represents feed costs which includes purchased concentrate and grass silage.

The model consisted of livestock component (representing dairy or beef production systems) which were constraint over limiting resources such as land, labor, feed, and replacement stocks. These limiting resources (except for land which was fixed) could be brought from external sources if farm's own resources were not sufficient to carry out farm activities. Labor used on farm was determined by balancing out labor requirement default values (28) for each of the animals on farm and total labor available on farm (i.e., family labor and hired labor if required). Similarly, total feed used on farm was determined based on energy and protein requirement of each of the animals on farm, feed produced on farm (grass, grass silage and grain silage) and feed (grass silage and concentrate feed) from external sources if required. The model assumed a 4-year production cycle for all livestock systems, where a minimum of 25% of animals were culled each year and replaced by either own farm-produced or bought-in replacements. Animal number on a particular year on farm was based on animal number on the previous year, culled animals and replaced animals. To determine calf numbers calving and mortality rates were included.

For dairy farms, total milk production was the summation of milk produced by all lactating cows and assumed to be sold to the market. There was no consideration for spillage, discards, or own consumption. All male calves born on farm were sold and considered as another output for dairy farms. For beef farms, the main outputs were calves, 18-month beef, 24-month beef and lambs (if the farm has a sheep production activity). Farm resources such as labor and feed required to produce these outputs were determined based on number of animals on farm each year.

The model was run under three scenarios; a baseline scenario *("baseline")* where farms were assumed to have disease-free production system and two disease scenarios; (i) a standard disease scenario *("disease")* with an assumption that a farm production system was under a standard prevalence rate of liver fluke and (ii) a climate change diseased scenario *("disease+cc")* where it was assumed that a farm had a "diseased production system" under climate change conditions. The farm net profit and production level under both disease scenarios were compared with corresponding outputs under the baseline scenario to determine the impact of the disease on farms.

Data Input

Farm Level Data

Farm level data were taken from the Scottish Farm Business Survey (FBS), a survey conducted annually in Scotland (18). The FBS collects physical and economic farm level data in a sample of around 550 representative farms each year. The sample data used in this paper contained 50 dairy farms and 110 beef farms which were studied separately to analyse economic impact of the disease between those two livestock production systems. The farm variability within a production system was considered by using farm profitability, where a comparison of the highest profit-making farms (top 25% farms) and the lowest profit making (bottom 25% of farms) was undertaken. Farm vulnerability (v_f) was determined using the ratio of farm support payment (S_f) on farm net profit (ρ_f). For this study, a farm (f) was considered vulnerable if total support payment (S_f) it received was higher than net farm profit, such as;

$$v_f \; if \; \frac{\rho_f}{S_f} < 1$$

Disease Parameters

The disease parameters (**Table 1**) used under the standard "*disease*" scenario for this study were taken from a Herd Partial Budget model (29) and a National Welfare model. The disease prevalence on dairy farms was estimated slightly higher (19.3%) than that on beef farms (13%). In the model, the loss in production and direct cost per infected animals were determined at UK-wide dairy and beef production levels. Loss in production included reduction in milk yield in case of dairy and reduction in carcass weight in case of beef animals. An increase in 1% of culling rate was also included in the model. The direct costs included veterinary and medicine costs and added to the variable costs of each of the infected animals.

TABLE 1 | Disease parameters used in the model.

Parameters	Dairy	Beef
Disease prevalence[a]	19.3%	13%
Loss in production[a]	7.7%	0.5%
Direct cost (£/infected animal)[b]	86.15	20.40

Source: [a]6; [b]30.

TABLE 2 | Change parameters used in the model under the "*disease+CC*" scenario compared to the *baseline* scenario.

Parameters	Change
Prevalence	+50%[a]
Grass production	+35%[b]
Direct costs	+10%[b]
Loss in production	−6%[c]

Source: [a]13; [b]32; [c]33.

Climate Change Parameters

The climate change "*disease+CC*" scenario used the A1B[1] emission scenario which was a part of UKCP09 using HadRM3 model (31). Disease prevalence under the climate change scenario was based on an earlier study (12) which used the Ollernshaw index to estimate disease risk in the UK under climate change. This disease risk under climate change scenario (a 50% increase in prevalence) was used as a proxy for disease prevalence under climate change in this paper (**Table 2**). This scenario includes climate change effects not only on the disease but also on the production system directly affecting individual animals. Two parameters, changes in grass production and loss in production due to heat stress were assumed to be the changes that affected individual production level of an animal under climate change. Grass yield change parameter was taken from our earlier study (32) which used a dynamic crop model, COUP (32) to simulate grass growth under climate change scenario. The production loss parameter due to heat stress was based on a study in the UK which looked at impact of heat stress on livestock farms (33). In addition to that, a small increase in direct variable costs under climate change was assumed (32). The additional direct costs include small adjustments made on farms to minimize heat stress such as providing additional water and increase in veterinary care.

RESULTS

Farm Variability

There was a significant difference between dairy and beef farms both in physical and economic terms (**Table 3**). On average Scottish dairy farms were significantly larger in terms of farm area, herd size, fixed costs and farm net profit than Scottish beef farms. Beef farms, however, received higher farm support

[1]A balanced emission scenario as defined by Intergovernmental Panel on Climate Change (30).

payments, which was almost three times higher than the farm net profit indicating a significant reliance on farm support payment.

Farm Net Profit

All sampled farms showed reduction in farm net profits under the standard "*disease*" scenario (light colored boxes in **Figure 1**). There was a small difference in the impact of disease on dairy and beef production systems with beef farms projected to have a smaller loss with an average reduction of 6% in farm net profit compared to dairy farms which were projected to lose on average 12%.

TABLE 3 | Average farm variables on Scottish dairy and beef farms (st. dev. in parenthesis).

Farm variable	Dairy $n = 50$	Beef $n = 110$
Arable land (ha)	15.5 (21.0)	7.5 (12.9)
Grass land (ha)*	143.2 (72.0)	120.9 (78.2)
Dairy/Beef Herd size (LU†)**	321 (151)	161 (108)
Sheep herd size (LU†)*	7 (10)	24 (11)
Family labor (hrs)	3,582 (1317)	3,124 (1068)
Stocking rate** (LU†/ha)	2.14 (0.8)	1.33 (0.5)
Milk yield (ltr/cow)	7,207 (1668)	na
Farm support payment[a] (£)**	38,011 (21,575)	54,993 (30,352)
Variable costs (£/cow)	240 (75)	245 (74)
Fixed costs (£)**	129,098 (61,880)	57,349 (91,773)
Farm net profit (£)*	40,468 (90,550)	29,018 (38,869)
Support payment share**	0.93 (1.61)	2.91 (9.8)

[a] *Farm support consists of direct farm payments and agri-environment scheme payments. Significant difference between dairy and beef farm variable at *$P < 0.05$; **$P < 0.01$ levels; †LU = livestock unit (34).*

There was, however, substantial increase in loss especially on beef farms when climate change effects are included. Under the "*disease+CC*" scenario (dark colored boxes in **Figure 1**), the average loss on dairy farms was projected to increase up to 24% and on beef farms up to 36%. There was also a higher variation of disease impact under the "*disease+CC*" scenario in beef farm group compared to that in dairy farm group.

The impact of disease on farm net profit was different between profitable and non-profitable farms. The differences in impacts of the disease between the profitable farms (Top quarter farms) and the non-profitable farms (Bottom quarter farms) were highly significant under both of the "*disease*" and "*desease+CC*" scenarios (**Table 4**). The top and bottom performing farms within beef farms, however, only showed a significance in difference in impacts of disease under the "*disease+CC*" scenario but not under the "*disease*" scenario.

Farm Production

In this analysis, change in livestock numbers on farms (number of lactating cows for dairy and number of suckler cows for beef

TABLE 4 | Percentage changes in farm net profit on farms in the top quarter and bottom quarter of dairy and beef farm groups compared to the baseline scenario.

Farm type/scenarios	Top quarter farms	Bottom quarter farms
Dairy		
*disease***	−7%	−23%
*disease+CC***	−11%	−37%
Beef		
disease	−4%	−7%
*disease+CC***	−5%	−95%

**$P < 0.01$.

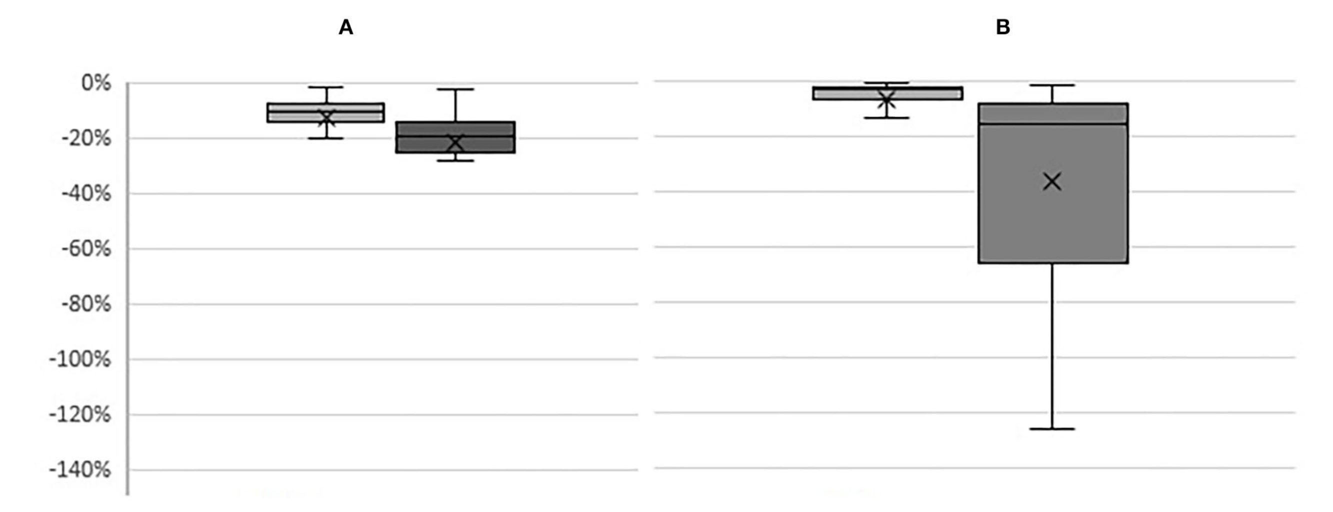

FIGURE 1 | Boxplots representing percentage changes in net profit on **(A)** dairy and **(B)** beef farms under "disease" and "disease + cc" scenarios compared to the baseline scenario; (line is the median and cross is the average value for each farm groups; y-axis represents percentage).

FIGURE 2 | Percentage change in animal numbers on dairy and beef farms under "*disease*" and "*disease+CC*" scenarios compared to the baseline scenario (y-axis represents percentage).

farms) is assumed to be representing change in farm production. Dairy farms were projected to reduce their production by 2.5% under the standard "*disease*" scenario and by 7% under the "*disease+CC*" scenario (**Figure 2**). Beef farms were expected to reduce animal numbers by 3% under the standard "*disease*" scenario but a substantial reduction was expected (44%) under the "*disease+CC*" scenario.

Farm Vulnerability

As shown in **Figure 3**, there were fewer dairy farms (16%) in the "vulnerable" category farms compared to those in beef farms (48%) in the baseline scenario. Under the "*disease*" scenario, there was a small increase in percentage of the number of vulnerable farms for both dairy (+6%) and beef (+3%) farm types compared to the baseline scenario. However, there was a substantial increase in percentage of vulnerable farms for both dairy farms (+20%) and beef farms (+27%) under the "*disease+CC*" scenario. This resulted in more than one-third of total dairy farms and three-fourths of total beef farms in the "vulnerable" category of the farms.

DISCUSSION AND CONCLUSIONS

Liver fluke infection has economic consequences on a livestock production system and due to unequivocal assumptions of future climatic conditions to be more favorable for the disease to flourish, we included climate change effects to examine the economic impact of the disease at a farm level production system. This means, our analysis not only included the effect of climate change on disease prevalence alone but also changes in grass production and livestock production due to heat stress.

The analysis shows a reduction in farm net profit of 12% on an average dairy farm and 6% on an average beef farm on a standard disease scenario. This reduction in profit increases by 2-folds for dairy farms and by 6-folds for beef farms when climate change effects are included. This highlights the importance of including climate change effects in ex-ante economic impact studies of liver-fluke disease. The difference in impact between dairy and beef farming systems is due to the variability in farm management and productivity in those two faming systems. An average dairy farm in Scotland is considered to be more efficient compared to an average beef farm (18). The impact of disease without climate change effects is lesser on an average beef farm compared to that on an average dairy farm due to a lower prevalence rate of disease, a smaller loss in production and a relatively lower average farm net profit on a beef farm. Higher disease prevalence for dairy farms compared to beef farms is due to the difference in location and farm management. Scottish dairy farms are mostly located in south west region which reported higher incidence of liver fluke than other regions (12). In addition, the Scottish beef farms have a more extensive production system than dairy farms which also contributes to a lower disease prevalence.

The impact of disease on beef farms increase substantially under climate change compared to that on dairy farms. Although, the climate change parameters are assumed to be same as in dairy production systems, an increase in

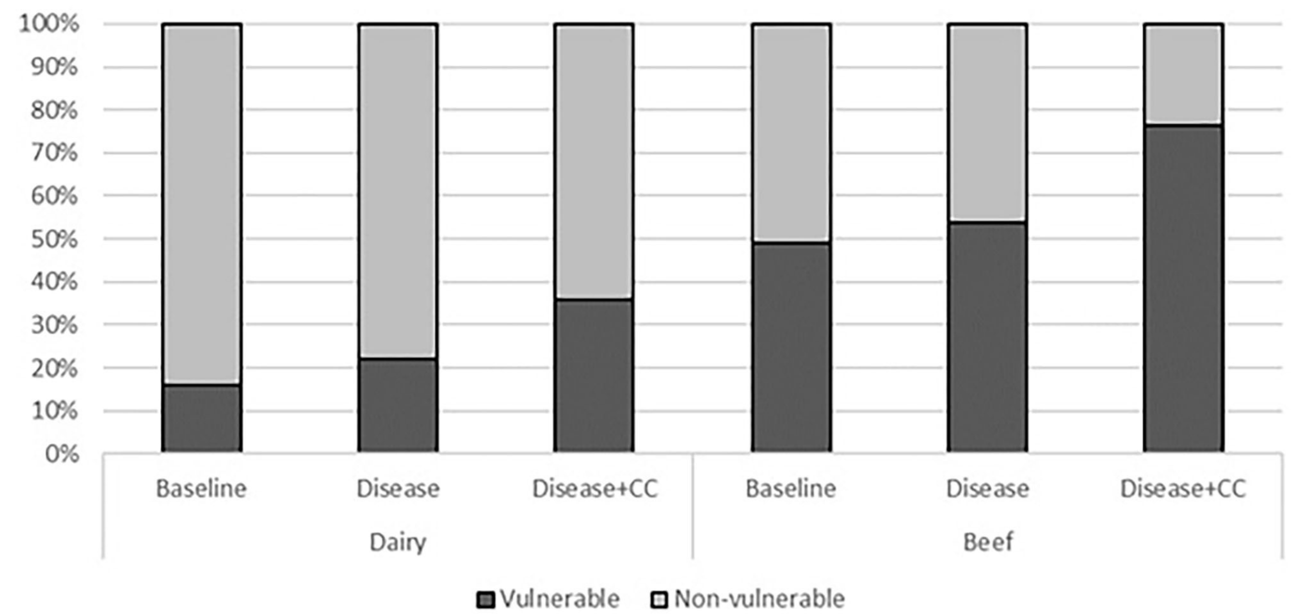

FIGURE 3 | Proportion of vulnerable and non-vulnerable dairy and beef farms (y-axis represents percentage).

marginal cost (due to increased variable cost) and decrease in marginal profit (due to larger loss in production) under climate change play a significant role in unbalancing farm net profit on beef farms. In the context of climate change, for almost half of the sampled beef farms, costs due to the disease make beef production unprofitable, leading farmers to substantially decrease their production. Some of these farms (41%) decreased their production to minimize losses. There was a small gain from increased grass production under climate change which was offset by the lower feed intake due to heat stress.

There is also a significant difference in the impact of the disease both with and without climate change effects between farms in the top quarter and bottom quarter in dairy farm group. It clearly highlights the importance of including farm variability within a farm type to conduct an impact assessment of farms. Many earlier farm level impact assessment studies analyzing economic impacts of external shocks such as change in policy and market prices presented similar conclusions (13, 14, 21). Within dairy farm types, the farms in the top quarter are more efficient producers and have higher profits than farms in the bottom quarter. Those farms have higher yielding animals, higher productivity and also receive higher price for their products. Although the disease effects were similar on those farms as to other farms, those farms are efficient farms and more capable of adjusting their systems (such as by purchasing less concentrates) to minimize the impact of the disease. The relative reduction in net profit due to disease on farms in the top quarter is hence smaller. Unlike dairy farms, there is a very small variability in impact of disease between beef farms under the standard "disease" scenario. Most of beef farms have smaller profits and the difference in profitability between farms in the top and bottom quarter is small, hence show relatively small variability in impact of disease. However, under "*disease+CC*" scenario, there is a substantial increase in variability in impact of disease between beef farms. Beef farms in the bottom quarter reduce their production significantly. These farms have larger reductions in net profit and the difference in impact of disease on these farms compared to farms in the top quarter becomes very significant.

There are almost half of beef farms that rely on farm support to be profitable (vulnerable farms) compared to only 16% of dairy farm with such vulnerability. The impact of liver-fluke on vulnerability is almost similar on both farm types. However, when climate change effects are considered, the disease increases vulnerable farms by 27% in beef farm group and 20% in dairy farm group. This means adding climate change effects to disease would substantially increase number of vulnerable farms in livestock production system.

The results and analysis presented in this paper are solely based on disease impact at farm level. The economic consequences of the disease on a livestock farm were assumed to be due to loss in production and increase in variable costs in this study. It should be noted that the disease has wider economic implications beyond the farm gate such as changes in market prices (35) due to reduced supply which might have additional effects on livestock farms.

DATA AVAILABILITY STATEMENT

The original contributions generated for this study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

SS is the main author of the paper. AB contributed in running the model and writing and analysis of the results. NF contributed in liver fluke prevalence work and writing and analysis of the results. BV contributed in result analysis and writing the paper. MH contributed in writing the paper and providing support to conduct this work. All authors contributed to the article and approved the submitted version.

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Emulating Agricultural Disease Management: Comparing Risk Preferences Between Industry Professionals and Online Participants Using Experimental Gaming Simulations and Paired Lottery Choice Surveys

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Mitigating the spread of disease is crucial for the well-being of agricultural production systems. Implementing biosecurity disease prevention measures can be expensive, so producers must balance the costs of biosecurity investments with the expected benefits of reducing the risk of infections. To investigate the risk associated with this decision making process, we developed an online experimental game that simulates biosecurity investment allocation of a pork production facility during an outbreak. Participants are presented with several scenarios that vary the visibility of the disease status and biosecurity protection implemented at neighboring facilities. Certain rounds allowed participants to spend resources to reduce uncertainty and reveal neighboring biosecurity and/or disease status. We then test how this uncertainty affects the decisions to spend simulation dollars to increase biosecurity and reduce risk. We recruited 50 attendees from the 2018 World Pork Expo to participate in our simulation. We compared their performance to an opportunity sample of 50 online participants from the survey crowdsourcing tool, Amazon Mechanical Turk (MTurk). With respect to biosecurity investment, we did not find a significant difference between the risk behaviors of industry professionals and those of MTurk participants for each set of experimental scenarios. Notably, we found that our sample of industry professionals opted to pay to reveal disease and biosecurity information more often than MTurk participants. However, the biosecurity investment decisions were not significantly different during rounds in which additional information could be purchased. To further validate these findings, we compared the risk associated with each group's responses using a well-established risk assessment survey implementing paired lottery choices. Interestingly, we did not find a correlation in risk quantified with simulated biosecurity investment in comparison to the paired lottery choice survey. This may be evidence that general economic risk preferences may not always translate into simulated behavioral risk, perhaps due to the contextual immersion provided by experimental gaming simulations. Online recruitment tools can provide cost effective research quality data that can be rapidly assembled in comparison to industry professionals, who may be more challenging to sample at scale. Using a convenience sample of industry professionals for validation can also provide additional insights into the decision making process. These findings lend support to using online experimental simulations for interpreting risk associated with a complex decision mechanism.

Keywords: experimental games, veterinary diseases, decision making, behavior, experimental economics, health economics, data science

1. INTRODUCTION

Disease outbreaks across livestock production systems can have devastating economic consequences. Porcine Epidemic Diarrhea Virus (PEDv), for example, is a coronavirus that costs the U.S. industry an estimated $900 million to $1.8 billion per year (1–3). Here, biosecurity refers to the initiative to stem the spread of disease in agriculture (4), which include a set of tools for disease prevention (i.e., vaccines) along with sanitary regulations and protocols that can mitigate disease transmission across production systems. Increased biosecurity reduces disease transmission between producers (5). However, biosecurity tools and practices vary in cost and perceived efficacy (6, 7). Hence, supply chain managers must balance the costs of biosecurity investments with the expected benefits of reducing the risk of infection. Our aim is to investigate the strategies used to achieve this balance, by quantifying risk mitigation behaviors associated with economic investment in biosecurity. Our research approach focuses on applying digital simulations for studying this decision making process.

Experimental gaming simulations, a branch of "serious gaming," are tailored interfaces that leverage software from game design to recreate a complex decision mechanism (8–12). Here we use simulations to collect decision making data and analyze responses with respect to various visual stimuli that are designed to communicate risk. This is our lab's primary tool for studying human behavior and how risk preference may influence the spread of disease among agricultural supply chains (9, 13–15).

Although biosecurity has been shown to reduce disease prevalence, widespread adoption of biosecurity varies, possibly due to uncertainty in efficacy and return on investment (7). Our experimental gaming simulation tests risk preference with regards to several scenarios in which disease prevalence and neighboring biosecurity visibility are varied. By injecting different types of uncertainty into experimental game simulations, we can explicitly observe response to uncertainty and how it may change as risk communication strategies adapt.

Our previous study (14) analyzed the risk associated with biosecurity investment decisions across a multitude of disease outbreak scenarios. Using a sample of 1,000 participants from an online survey recruitment marketplace, Amazon Mechanical Turk (MTurk), we found three prominent risk strategies—risk tolerant, opportunistic, and risk averse—by analyzing responses with regard to disease threat. We then investigated how information uncertainty affects the decision making process, by varying the visibility of the disease spread and biosecurity protection across each simulated population of farms (13, 14). Among this sample, we found that high visibility in disease spread led to more risk averse behaviors while high visibility in biosecurity status led to more risk tolerance. We also investigated how risk preference may differ among a sample of industry professionals and stakeholders. We attended the 2018 World Pork Expo, the world's largest pork industry trade show attended by thousands of producers and industry professionals (https://worldpork.org/about-expo/all-about-expo). Here, we recruited 50 attendees to complete our experimental gaming simulation. Their performance was then compared to 50 MTurk recruits, in addition to the 1,000 recruits sampled in (14). When aggregating across all experimental outbreak scenarios, we did not find a significant difference in biosecurity investment risk distributions. In this work, we aim to further investigate potential differences in risk preference among World Pork Expo participants and online recruits from MTurk. We compare biosecurity investment decisions during each set of experimental scenarios as well as the willingness to spend economic resources to reduce uncertainty.

We also compare our sampled participants' behavior using a well-established risk assessment survey using paired lottery choices (16). This context-free, multiple price list approach (17) measures risk aversion with respect to economic preference by varying the probability of a high and low payout. Using their choices, participants can then be categorically grouped into "Risk Seeking," "Risk Neutral," or "Risk Averse." The main difference between this paired lottery choice assessment and our experimental gaming simulations is the context surrounding the decision making process. The paired lottery choice assessment attempts to measure underlying preferences in a purely economic trade-off. Whereas the economic risk management associated with biosecurity investment decisions are specifically framed in the context of agricultural outbreak mitigation. We compare risk preferences associated with lottery choices against simulated biosecurity investment strategies between World Pork Expo participants and MTurk recruits.

Several studies investigated how risk aversion delineated using this paired lottery choice assessment (16) have compared to real world behaviors. Experimental market trading behaviors were found to correlate with paired choice lottery risk aversion (18). Negative health related behaviors including cigarette smoking, heavy drinking, obesity, and seat-belt non-compliance were found to be anti-correlated with surveyed risk aversion (19). Similarly, a generalized self-assessment risk survey could predict surveyed lottery risk aversion (20). These contexts based risk aversion measures were actually in some cases better predictors of malbehaviors in comparison to multiple price list assessments (21). This difference in performance may be attributed to additional background information captured regarding the individuals' preferences using context based measures of risk aversion.

Providing contextual background to the studied decision making process can have a pronounced effect on risk mitigation. For example, the domain specific risk-taking scale (DOSPERT) (22) is a context driven risk assessment questionnaire which has shown promising results in characterizing risk averse behaviors across several content domains. This flexible measurement is useful for categorizing risk with respect to content areas in which individuals may exhibit various levels of risk aversion depending on the framing. Context based risk assessments can provide additional insights into behavioral response and how risk may fluctuate with respect to situational framing.

Our experimental gaming simulation exemplifies this initiative for capturing contextually driven risk mitigation behaviors. We found that risk aversion characterized by multiple choice lottery assessment differed from risk associated with behaviors in our simulated environment. This supports the argument that context driven risk assessment may be more appropriate for identifying behavioral risk regarding specific domains. Capturing these nuanced behaviors may prove illusive in the lens of traditional multiple price list risk assessment frameworks.

Our previous findings (14) did not detect a difference in biosecurity investment decisions between World Pork Expo attendees and recruits from MTurk. However, aside from biosecurity investment, other behavioral aspects may differ between these cohorts. Our current study investigates how Pork Expo attendees and online recruits from Amazon Mechanical Turk may diverge in their decision making with respect to each tested experimental scenario. Although we previously found the overall distributions of risk were comparable between Pork Expo and MTurk groups, it is also important to highlight where there may be differences in simulated behavior. This validation process is necessary when recruiting large convenience samples from online survey marketplaces.

Along with the ability to invest in biosecurity, our simulation allowed participants to purchase information to reduce uncertainty in the decision making process by revealing infection and biosecurity status of neighboring facilities. Due to expo attendees' industry knowledge and expertise, we may expect to find a measurable difference in their willingness to purchase information in comparison to a opportunity sample of online recruits. We also investigate whether Pork Expo participants' biosecurity investment strategies and experimental earnings (i.e., their performance) differed across each particular experimental scenario. This leads to our first tested hypothesis:

> (H1): Participants with industry knowledge will invest more experimental resources to procure information and reduce uncertainty in the decision making process.

In addition, we compare risk associated with simulated biosecurity investment to risk aversion measured using a paired lottery choice survey (16). The paired lottery choice survey has a well-defined payoff function where economic benefit and risk are clearly established during each decision. Our experimental simulation's risk decision tradeoff is more obscured by visual assessment, assumptions regarding disease spread, and protection offered by neighboring facilities' biosecurity implementation. Our study investigates how these two risk assessment frameworks align. (23) found real-world farmer production risk, as formulated by (24), correlated with paired lottery choice risk aversion. We may expect that participants who invest more simulated resources in biosecurity would behave with more risk aversion in the paired lottery choices. We formulate this hypothesis (which we later reject) as:

> (H2): More investment in simulated biosecurity will correspond with more risk aversion in the paired lottery choice assessment.

2. METHODS

We created a digital application to assess the impact of economic consequences on decisional risk. The experimental gaming simulation and risk assessment survey were engineered using the Unity Development Platform. The final application was deployed using WebGL (25) and hosted on the University of Vermont's web server, where simulation decision data were stored in a relational database. The 2018 World Pork Expo participants completed the experiment in our booth using provided tablet computers. The 50 online participants were contracted using Amazon Mechanical Turk and compensated through Amazon with a base pay of \$2.00 USD for successfully completing the assignment along with a bonus payment based upon their simulation performance. On average MTurk participants earned an additional \$7.93 ($\sigma = \$4.98$) and completed the experiment in 10.92 min ($\sigma = 4.80$ min), after the introductory on-boarding. We paid the participants at the World Pork Expo a higher rate to bolster attendance and interest. Pork Expo participants earned on average \$16.11 ($\sigma = \$4.26$) over 15.97 min ($\sigma = 4.91$ min) to complete the simulation and survey. These monetary incentives are crucial to our experimental design and have been found to increase salience and immersion in the decision making process (26, 27).

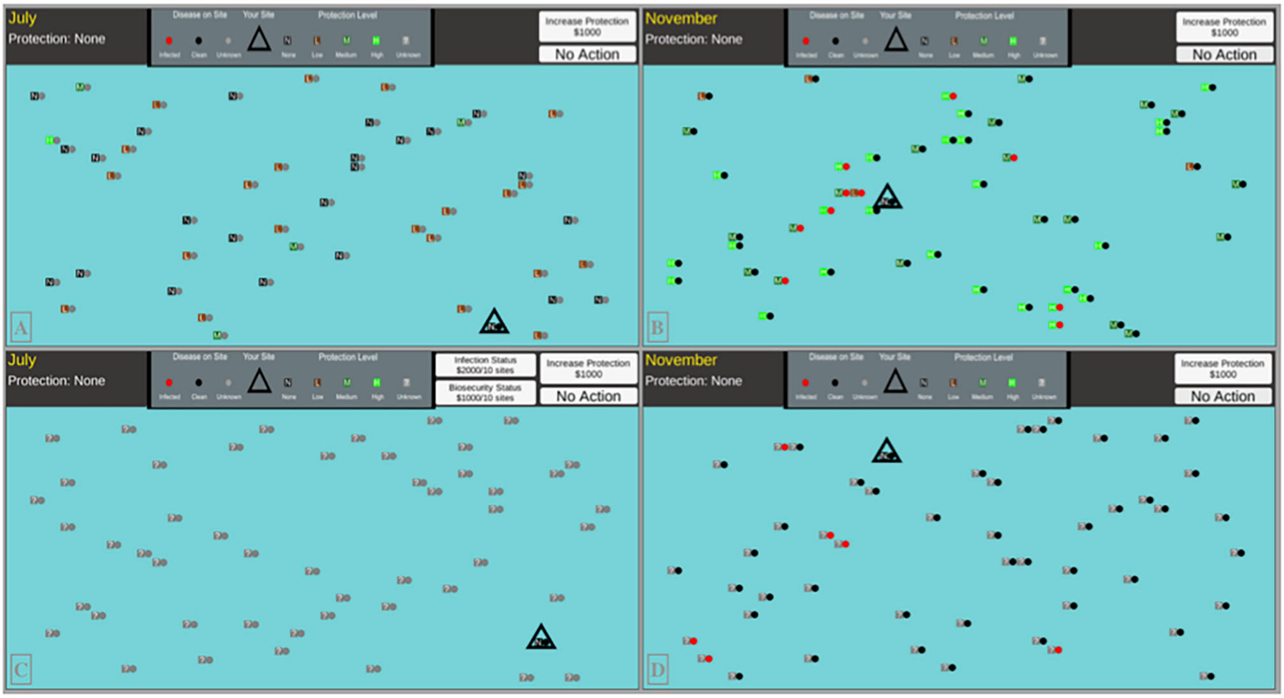

FIGURE 1 | Simulation interfaces for a sample of our experimental treatment scenarios: **(A)** High Disease Uncertainty, No Biosecurity Uncertainty **(B)** No Uncertainty **(C)** Full Uncertainty, Option to pay to reveal disease and biosecurity status **(D)** High Biosecurity Uncertainty, No Disease Uncertainty. Every combination of these information treatments were tested.

2.1. Biosecurity Investment Experimental Game

Our methods were derived from the online experimental simulation featured in (13). The experimental game allowed participants to allocate simulated resources toward biosecurity investment during disease outbreak scenarios with disease spreading across a production system. Each experiment began with an introductory slide show, which framed the study design and informed the player of the game mechanics and interface. The game introduction slideshow can be found in (14). We obtained informed consent from each participant, during our prepared introductory slide presentation prior to the experiment. These practices were accepted by the University of Vermont Institutional Review Board concerning experiments using human participants (University of Vermont IRB # CHRBSS-16-232-IRB).

Each of our 50 industry participants and MTurk online participants completed 32 simulated outbreak scenarios (i.e., 6 month decision years), for up to 192 decisions per person (depending upon infections). We collected a total of 18,716 decisions to compare (9437 Pork Expo; 9279 MTurk). Numbers differ slightly because decisions during a round would be truncated if the participant's facility became infected. Each round of decision making featured adaptations to the interface and/or information regarding the infection status and biosecurity allocation among the population of farms (see **Figure 1**). The participant is in charge of a single production facility, surrounded by 50 computer-controlled facilities. Every round consists of six decision months in which players have the choice to invest their simulation dollars in more biosecurity for their own facility. The simulated dollars earned were converted to U.S. currency after completion of the experiment. Online recruits were compensated at a rate of $1 USD to $23,500 simulation dollars, on top of their base pay of $2.00 USD for completing the assignment. Participants from the World Pork Expo were paid a rate $1 USD to $12,000 simulation dollars.

Biosecurity investment reduces the probability of infection. Players could sequentially increase their biosecurity status once per each of the six decision months at the cost of $1,000 simulation dollars, from "None" to "Low" to "Medium" and a maximum of "High." In our simulation, each successive level of biosecurity implemented reduces the probability of infection by 25%. If the player did not wish to invest in biosecurity, they could choose "No Action" to continue to the next decision month. At the end of each decision month, the infection could progress to any production facility with a varying infection rate probability (p_{inf} = 0.15) that decreased with distance from the infection source. Explicitly, the raw probability of transmission between an infected facility and a clean facility separated by distance, D, would be calculated as $\frac{p_{inf}}{D^2}$, which was then adjusted by the clean facility's biosecurity level. If the player's facility became infected, the round would immediately end and the player would lose $25,000 simulation dollars. For each consecutive round, the participant's biosecurity status was reset to "None" and the

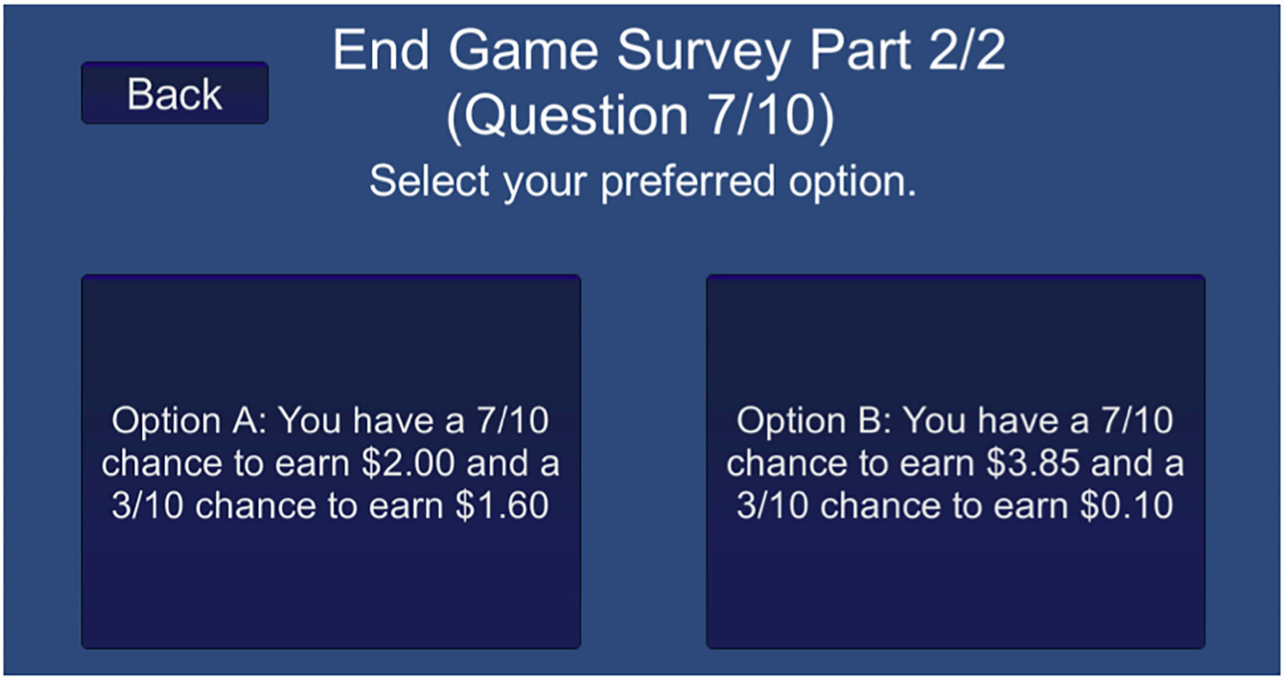

FIGURE 2 | Paired lottery choice risk Assessment interface: a sample of the menu design of the paired lottery choice survey.

infection and neighboring set of farms were re-initialized by randomly reassigning the geographical positions and biosecurity status of each facility.

One quarter of all rounds presented full visibility of the infection status and neighboring biosecurity to the player. The other 75% of tested treatments injected uncertainty into this decision mechanism by cloaking the infection status and system-wide biosecurity configuration. Additionally, certain rounds featured the capability to purchase more information regarding the infection status and/or biosecurity allotment for 10 neighboring facilities. The cost for revealing this information varied between either $1,000 or $2,000 simulation dollars. Examples of our user interface (UI) for a sample of our information treatment types are given in **Figure 1**.

2.2. Paired Lottery Choice Risk Assessment

We created a digital version of the risk assessment paired lottery choice survey featured in (16). Participants are instructed to choose their preference across ten distinct paired lottery choices. Each pair of choices features a safer "Option A" in comparison to a more risky "Option B," which has a higher pay gap between the two reward probabilities. For example, the first choice features Option A as a 1/10 chance to earn $2.00 and a 9/10 chance to earn $1.60, while Option B presents a 1/10 chance to earn $3.85 and a 9/10 chance to earn $0.10. Here, only the most risk tolerant of individuals may consider choosing Option B over Option A. This probability gap between the higher and lower payment for each choice sequentially increased, such that the more risky option becomes more viable as the survey progresses (i.e., the expected payoff of Option B becomes greater than the expected payoff of Option A). By choice 7, the payout probability is now 7/10 for each high reward and 3/10 for the low reward (see **Figure 2**). Here, it becomes somewhat ambiguous which is the more appropriate option, creating an interesting risk dilemma to study.

A natural "crossover point" occurs where a rational individual may move from choosing the safer Option A to a more risky Option B. We quantify risk using the ratio that "Option A" was chosen over the ten paired lottery choices. Participants had the option to revise their choices up until their final decision, after which a random number generator was used to select one of their decisions and then determine their reward. Randomly implementing one of their choices insured that every choice was incentive-compatible, meaning that participants had an incentive to reveal their true preferences. Our digital interface of this paired lottery survey featured in our simulation is provided in the **Supplementary Material**.

In this portion of the study, we also compensated volunteers from the 2018 World Pork Expo a slightly higher rate: Option A $2.00 USD or $1.60 USD; $3.85 USD or $0.10 USD. Online recruits were paid either $0.60 or $0.50 for Option A or were paid $1.10 or $0.05 for Option B.

2.3. Statistical Methods

In our simulation, each decision whether or not to invest resources in biosecurity has an associated financial risk. We implemented a biosecurity investment rating, R_i defined in (14) for each participant i. This is the weighted average of the player facility biosecurity status across a set of decision months. For each round, the biosecurity status (0 = "None," 1 = "Low," 2 = "Medium," 3 = "High") of the player's facility is tallied and then normalized by the total number of decisions. For example, suppose for one round, participant j invested experimental dollars to obtain "Low" biosecurity in month 3 of 6 and then "Medium" biosecurity on month 5 of 6. Then $R_j = 1.0 = \frac{1}{6} \cdot [0 + 0 + 1 + 1 + 2 + 2]$. More biosecurity reduces the risk of infection. Hence, a higher biosecurity investment rating is associated with more risk averse behaviors, which is an indication of participants' risk preference.

Risk aversion in the paired lottery choice survey was measured using the number of "safe" (Option A) choices registered by each participant and then normalized by their total number of decisions. For example, if a participant chose Option A 4 times out of 10, their surveyed risk aversion score is 0.4, which would be considered "risk neutral" behavior. More than 4 safe choices correspond to more risk averse behavior while less than 4 choices designate risk tolerant behavior. We chose this risk metric to be consistent with (16).

Statistics were performed using Python 2.7 SciPy statistical libraries (28). The two-sample Kolmogorov–Smirnov (KS) test (29) was implemented to compare risk lottery preferences for consistency with (16). To quantify differences in risk aversion with respect to biosecurity investment ratings between sampled participants, we performed one-tailed Mann–Whitney U-tests (30). We chose the U-test since in our previous study (14) we found that the biosecurity investment ratings failed the D'Agostino and Pearson's test for normality (31, 32). Preferential risk distributions were displayed using violin plots (33). We tested statistical correlations between risk associated with simulation decisions and the risk preference lottery using Spearman's rank (r_s), correlation coefficient (34).

A demographic comparison between the World Pork Expo and MTurk cohorts are given in the **Supplementary Materials**. Demographic categorical frequencies comparing age, gender and education between samples were differentiated using the Chi Square (χ^2) statistical test (35). We did not find evidence that demographics effected the decision-making process.

3. RESULTS

We compare the decisions from 50 industry professionals and stakeholders from the 2018 World Pork Expo to 50 MTurk online participants. Additionally, we measured participants' risk preferences using the paired lottery choice assessment distributed in our exit survey, and noted how these preferences contrast with risk behaviors quantified using simulated biosecurity investment management.

3.1. Biosecurity Investment Simulation

We compared the distributions of biosecurity investment ratings between each set of participants using two-tailed Mann–Whitney U-tests across each treatment. We did not detect a difference in the distribution of biosecurity investment decisions between Pork Expo participants and MTurk recruits. We summarize these findings in **Table 1**. We also compared the session profit (i.e., overall simulation dollars earned) between samples and did not find a significant difference in earnings: PE [$\mu = 163{,}740.00$; $\sigma = 48{,}997.07$; min = 44,000; max = 258,000], MTurk [$\mu = 172{,}620.00$; $\sigma = 38{,}612.89$; min = 91,000.00; max = 263,000.00]: U = 1,095.0, $p = 0.2867$ (two-tailed).

TABLE 1 | Experimental treatment comparison.

Treatments	Biosecurity (μ, σ)		U	p-value
	PE	MTurk		
All	(1.38, 0.67)	(1.43, 0.72)	1214.5	0.68
Din Visible	(1.45, 0.67)	(1.56, 0.71)	1157.0	0.42
Bio Visible	(1.41, 0.65)	(1.23, 0.72)	1445.0	0.24
Bio Hidden	(1.33, 0.73)	(1.56, 0.75)	1046.5	0.12
Bio Reveal	(1.39, 0.71)	(1.46, 0.78)	1211.0	0.66
Dis Hidden	(1.37, 0.71)	(1.43, 0.76)	1178.0	0.51
Dis Reveal	(1.35, 0.72)	(1.36, 0.78)	1266.5	0.97

Biosecurity Investment ratings per experimental scenario delineated for each sample of 50 participants, Pork Expo (PE) and Mechanical Turk (MTurk). Comparisons are given for each set of Disease (Dis) and Biosecurity (Bio) visibility treatments, along with rounds in which participants can spend resources to reveal information regarding the infection and/or biosecurity. Using two-tailed Mann–Whitney U-tests, no significant differences were found in biosecurity investment across each set of experimental scenarios.

Although we did not find a significant difference between biosecurity investment distributions or performance, we did, however, detect a difference in the willingness to purchase information regarding biosecurity and infection status. To investigate hypothesis (H1) we tested two price levels, {$1,000, $2,000}, for revealing the biosecurity rating or infection status of 10 neighboring facilities. Comparatively, both groups invested more resources in infection status information: Expo total $401,000 (averaging $8020/person) v. MTurk total $316,000 (averaging $6,320/person). Overall, less resources were spent on biosecurity information, however with a larger division between cohorts: Expo total $256,000 (averaging $5,120/person) v. MTurk total $119,000 (averaging $2,380/person). We then quantified this difference in choices per participant between samples using the Mann–Whitney U-test.

We found that the Pork Expo group chose to spend significantly more money to reveal both biosecurity and infection data than MTurk participants, when the price was $1,000 per reveal. The difference in biosecurity spending was highly significant ($p = 0.0013$), while the difference in infection reveals was marginally significant ($p = 0.0487$). However, if we consider the power of the disease status result by adjusting the p value to control for the false discovery rate (36) due to performing 4 statistical tests, we find, ($p_{adj} = 0.078$), suggesting more sampling may be required for verification. However, the difference in biosecurity information spending between groups was highly significant, even after adjustment ($p_{adj} = 0.005$). In **Figure 3**, violin plots show each distribution of information reveal choices ($1,000) per participant for disease status (orange) and biosecurity (blue). There was no significant difference between groups in spending to reveal biosecurity ($p = 0.0587$) or disease ($p = 0.2835$) information when it cost $2,000 per

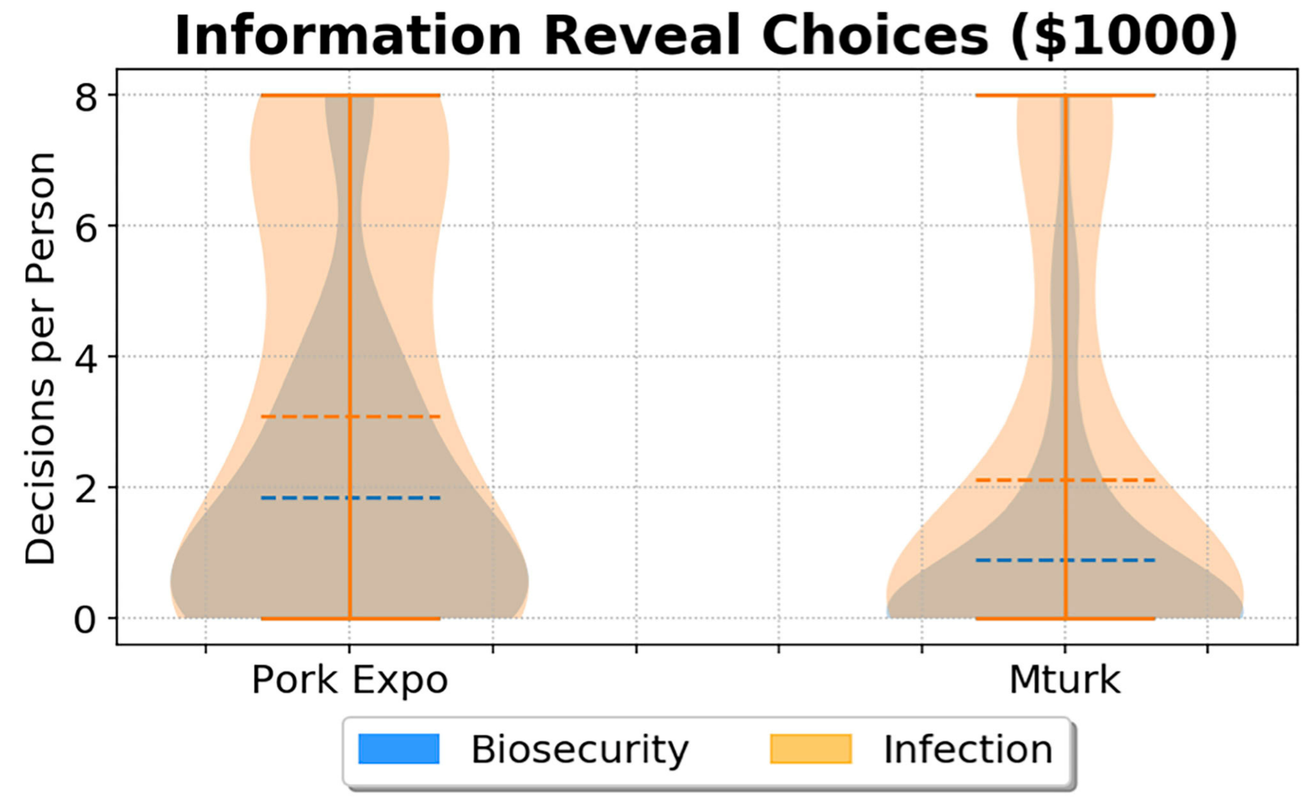

FIGURE 3 | Information reveal choice comparison ($1,000/reveal) between 2018 World Pork Expo (PE) participants and Amazon Mechanical Turk (MTurk). For each group, per person choices to reveal biosecurity (blue) are overlaid with choices to reveal disease statuses (orange). The dotted line denotes the mean of each distribution. For this experimental treatment, Pork Expo participants paid to reveal information more often than MTurk participants.

reveal (i.e., twice the price of increasing biosecurity). The results from each Mann–Whitney U-test per experimental treatment are given in **Table 2**. These results support hypothesis (H1) that participants with industry knowledge will invest more resources to reduce information uncertainty, given the stipulation that pricing motivates differences in this decision mechanism.

We also considered the relationship between information uncertainty reduction and biosecurity adoption. We may expect that more risk aversion would be associated with more choices to reveal information, however this was not supported by the data. Quite conversely, we actually found a moderately strong negative correlation from the MTurk cohort during both infection uncertainty experimental treatments ($1,000,$2,000) for participants who chose at least 1 infection information reveal: [Spearman $rho = -0.463, p < 0.01, N = 30$]. For these treatments, recruits from MTurk who revealed more infection information tended to adopt less biosecurity. Interestingly, we did not find evidence for this relationship from Pork Expo attendees who chose at least 1 infection information reveal: [Spearman $rho = 0.014, p = 0.93, N = 36$]. This highlights another interesting difference between these groups. Perhaps, for this subset of industry professionals, investing in additional information did not deter their initiative to situationally adopt biosecurity, whereas MTurk recruits may have been more motivated for maximizing their earnings when investing in reducing uncertainty. We did not find any significant correlation between risk associated with biosecurity adoption and number of biosecurity information reveals from either cohort.

TABLE 2 | Reveal treatment comparison.

Treatment	Reveals (μ, σ)		U	p-value
	PE	MTurk		
Inf $1,000	(3.10, 3.07)	(2.12, 2.93)	1481.5	**0.0487**
Inf $2,000	(2.46, 2.88)	(2.10, 2.81)	1330.0	0.2835
Bio $1,000	(1.84, 2.27)	(0.90, 1.77)	1651.5	**0.0013**
Bio $2,000	(1.64, 2.52)	(0.74, 1.23)	1455.5	0.0587

Choices (per person) to invest economic resources to reveal biosecurity (bio) and infection (inf) status for 2018 World Pork Expo Participants (PE) and Amazon Mechanical Turk (MTurk). We found Expo participants chose (highly) significantly more biosecurity statuses reveals and (marginally) significantly more infection status reveals when the cost was $1,000/reveal (bold). No significant difference was measured when the cost of revealing this information increased to $2,000 simulation dollars.

To further investigate this relationship between information uncertainty reduction and biosecurity adoption, we compared the risk preferences of participants who were willing to invest resources in reducing information uncertainty compared to those who opted out and never revealed infection and/or biosecurity statuses. Applying Mann–Whitney U-tests, we did

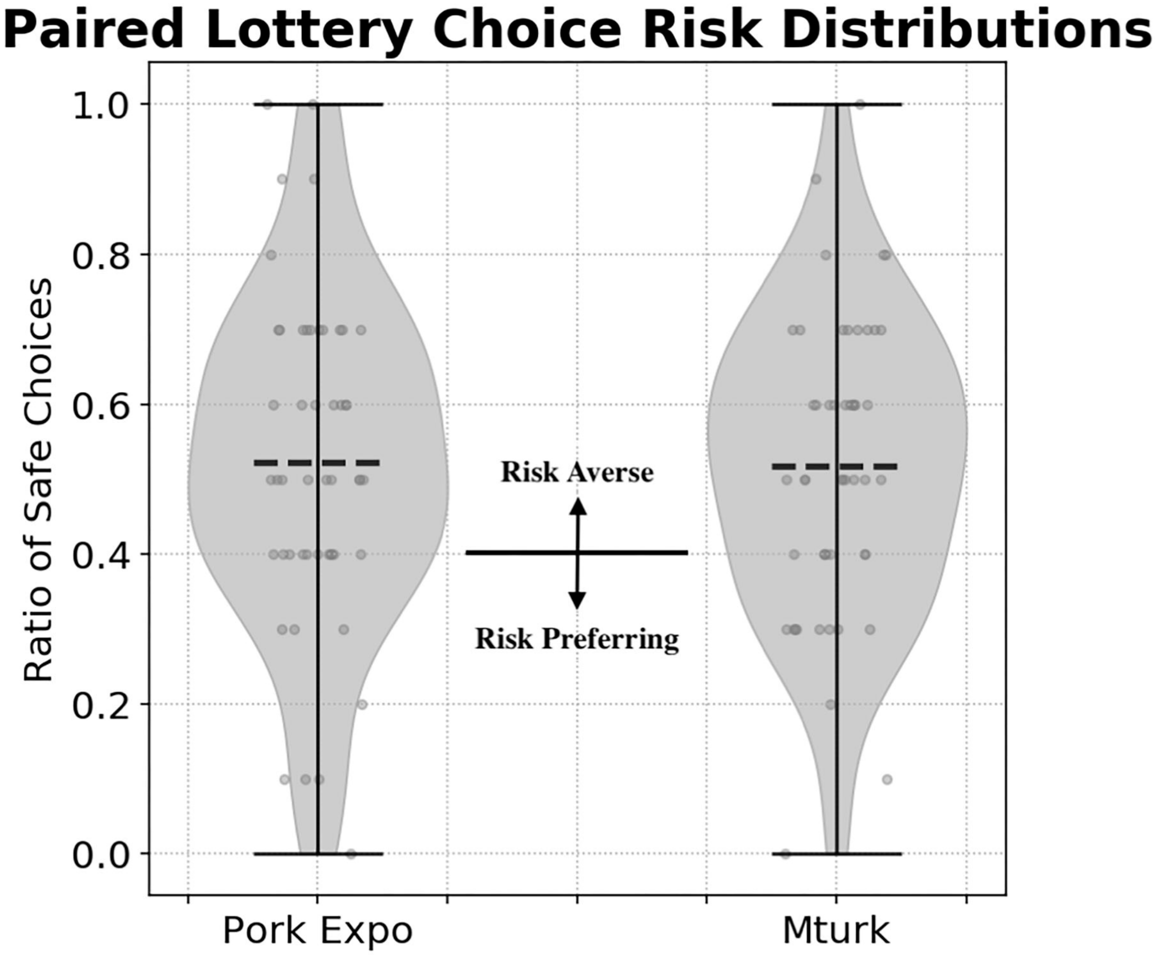

FIGURE 4 | Paired lottery choice survey risk preferences distributions comparing participants from the 2018 World Pork Expo and Amazon Mechanical Turk. The dashed line represents the mean from each distribution. The solid line at 0.4 (i.e., 4/10 safe choices) denotes risk neutral behavior. Making more than 4 safe choices is considered risk averse behavior while less than 4 safe choices is considered risk tolerant.

not find significant differences in biosecurity adoption between Pork Expo participants who chose to reveal infection/disease information and those who did not. In the MTurk cohort, we did find that recruits who chose to reveal information adopted less biosecurity for the $1,000 biosecurity reveal treatment [$U = 167, p < 0.05 : \mu_1 = 1.041, N_1 = 16$ v. $\mu_2 = 1.584, N_2 = 34$] and the $1,000 infection reveal treatment [$U = 225, p < 0.05 : \mu_1 = 1.240, N_1 = 26$ v. $\mu_2 = 1.595, N_2 = 24$]. This supports our previous finding that MTurk recruits may have been more reluctant to diminish their potential earnings, while Pork Expo attendees did not sacrifice biosecurity investment when also purchasing additional information.

3.2. Paired Lottery Choice Risk Comparison

We compared risk preference distributions between Pork Expo participants [$\mu = 0.522, \sigma = 0.219, \text{median} = 0.500$] and online recruits from Amazon Mechanical Turk [$\mu = 0.518, \sigma = 0.199, \text{median} = 0.500$]. Using a KS test, we did not find a significant difference in risk distributions between each sample : KS [$U = 0.06, p = 0.999, n_1 = n_2 = 50$]. In **Figure 4**, the risk preference distributions compare choices from each sample. As defined in (16), a risk neutral preference is defined as 0.4 (4/10) safe choices (i.e., "Option A"). More than 4 safe choices are deemed as risk averse, while less is considered risk tolerant. Under this metric, the majority of participants in both samples were categorized as risk averse. For Pork Expo participants, 31 (62%) were classified as risk averse, 8 were risk tolerant (16%), and 11 were risk neutral (22%). Mechanical Turk recruits followed a similar distribution: 32 Risk Averse (64%), 11 Risk Tolerant (22%), and 7 were risk neutral (14%).

We also considered the consistency in selections between each group of participants. We would expect that the majority of participants would begin with the safe "Option A" before eventually switching to the more risky "Option B" for the remainder of the survey. In (16) the majority of participants only switch once from "Option A" to "Option B," however there were cases of multiple switching from their sampled participants. We found the majority of our participants also only switched their responses one time. From the Mechanical Turk group, 2 participants (4%) didn't switch, 44 participants (88%) switched once, 2 participants (4%) switched twice, 1 participant (2%) switched 3 times, and 1 participant (2%) switched more than 3 times. The majority of the Pork Expo attendees also only switched once, however there were more cases of multiples switches: 3 participants (6%) didn't switch, 30 participants (60%) switched once, 6 participants (12%) switched twice, 5 participants (10%) switched 3 times, and 6 participants (12%) switched more than 3 times.

We investigate hypothesis (H2) by comparing risk associated with simulated biosecurity investment to decisions in the paired lottery choice assessment. We did not find a direct correlation between risk preference and biosecurity investment strategies for either sample: (Spearman) Pork Expo $r_s = 0.086, p = 0.54$; MTurk $r_s = 0.218, p = 0.12$; All $r_s = 0.142, p = 0.156$. We considered differences between simulated biosecurity investment with respect to risk classification under the preferential lottery (risk averse vs. risk tolerant in **Figure 4**), however since the majority in each group were risk averse, we could not reliably test this significantly. Given these results, we couldn't find evidence to support hypothesis (H2), that risk associated with our simulation will correspond with paired lottery choice assessment.

4. DISCUSSION AND CONCLUSION

To further explore potential differences in decision making between industry professionals and online recruits, we analyzed their choices regarding paying to gain situational awareness in an experimental game and their decisions in a paired lottery choice survey. We wanted to understand the magnitude of these differences to be able to determine the sample size needed to quantify efficacy of risk communication strategies. We did not find a measurable difference in the distributions of biosecurity investment decisions between World Pork Expo participants and online recruits from Amazon Mechanical Turk across each set of experimental information treatments.

We observed a difference in the willingness of participants to purchase information regarding neighboring infection and biosecurity status. In support of hypothesis (H1), we found participants from the World Pork Expo chose more often to reduce uncertainty in this decision making process. We note cost was a motivator in this decision making process, and at higher costs we found no significant differences in purchasing disease or biosecurity information. The most pronounced difference was the amount of spending by Pork Expo participants on neighboring biosecurity status information. Overall, both groups invested the most resources on reducing uncertainty around disease spread. Pork Expo participants, perhaps due to their industry profiles, had significantly more interest in neighboring biosecurity configurations than MTurk recruits. This distinction may indicate that reducing uncertainty regarding the spread of disease and neighboring biosecurity protection is of particular interest to industry professionals when weighing their risk of infection throughout this decision making process.

Interestingly, we did not find a direct association between lottery risk preference and biosecurity investment decisions, leading us to reject hypothesis (H2) for this sample of participants. One possibility for this lack of consistency in observed behaviors across the two risk assessment methods is the contextual framing that's motivating decisions within the experimental gaming simulation. The lottery risk preference may be contrasted as a measure of pure economic risk preference. Our simulated environment creates a more complex and realistic economic dilemma to tackle. This difference is especially highlighted during rounds that inject additional uncertainty in the decision making process by masking the spread of infection and/or shielding neighboring biosecurity configurations. This provides support for harnessing experimental gaming simulations to study behavioral risk. Experimental gaming simulations may be especially useful for emulating complex decision mechanisms in which nuanced behavioral signals may be difficult to capture using generalized risk assessment survey strategies. Further investigation is needed to accentuate these differences in behavioral responses associated with added contextual framing provided by experimental simulations, in comparison to traditional survey methods for measuring risk preference.

Overall, the distributions of risk associated with our biosecurity investment simulation were statistically comparable to our sample of 50 industry professionals and stakeholders from the 2018 World Pork Expo. Additionally, we found no difference between these two audiences in their performance from the lottery risk preference assessment portion of the experiment. Our findings lend support to using large samples of online recruits, such as MTurk, for identifying general trends in risk attitude and perception. Validation using a sample of participants with related industry knowledge provides confidence for behavioral analyses using experimental gaming simulations.

Potential bias in our results stem from Mechanical Turk participants completing this experiment fully digitally, while participants from the World Pork Expo underwent the simulation in-person during their attendance at the event. The payment scale was the only adjustment between administered digital application interfaces. Differences we are finding in strategies could be affected by Pork Expo attendees' current immersion in the subject material. This may also strengthen our result that the risk distributions with regards to biosecurity investment were similar. We also were limited by our sample size, as recruiting industry professionals is challenging in comparison to online survey marketplaces like MTurk. Hence, it is possible that a larger sampling of participants with an industry background are required to detect differences in behavior. These relationships between industry professionals and online recruits should be further validated when analyzing risk preferences associated with industry-specific decision making.

While comparing decision consistency in the paired lottery choice portion of the risk assessment, we found more Pork Expo participants ($\approx$ 40%) switched more than once between the safer "Option A" and more risky "Option B" in comparison to the MTurk sample. This is slightly more switching than may be expected. Perhaps this could have been due to survey fatigue, as the Pork Expo attendees were attending the fair recreationally, whereas the MTurk recruits were seeking an employment opportunity. Also, the final lottery choice sets the high payouts for both Option A and Option B at 10/10, so the most rational decision is to choose Option B for this last question. Although the vast majority of participants from both cohorts finished with "Option B," there was 1 case from the MTurk group and 8 cases from the Pork Expo attendees ending with "Option A." This difference could also be a sign of potential survey fatigue, or a misunderstanding of the lottery payouts for the final question. Overall the proportion of safe choices between each cohort was comparable and hence this metric for risk aversion was ideal for comparing behavior.

The decision-making data collected from experimental gaming simulations is not only informative in itself but also a valuable resource for disease-spread models lacking a human behavioral component. For example, agent based models (ABMs), (37), are computer simulations that can help forecast outcomes of decisions and interactions of entities (or agents) and their impact on the system. Agent based modeling has been applied to agriculture for producer decision interaction, (38), technology and policy modeling, (39), as well as for water management (40). ABMs can provide insights into epidemiological factors that exacerbate disease spread and their economic impacts on agricultural supply chains (41, 42). Human behavioral components, captured using digital experimental simulations, can then be used to model systemic outbreaks and how disease spread will change as human behavior is altered or risk communication strategies are devised (43). The distributions of behavioral risk observed in our biosecurity experimental gaming simulations can be embedded in these agent based models to test how proportions of risk aversion effect the spread of disease. The model can then be calibrated using real world estimates of viral incidence. Experimental gaming simulations can also provide insights into how individuals may adapt their risk preferences over time. Individuals may learn to become more or less risk averse in response to their simulated outcomes. Studying how different proportions of these risk attitudes effect the spread of disease can help gain insights into forecasting economic impacts and how different risk landscapes impact the well-being of the system. This may be useful to policy regulators interested in developing and testing risk communication strategies that nudge behaviors toward more risk averse disease management practices to help stem the spread of disease.

Experimental gaming simulations are effective tools for examining behaviors surrounding risk associated with agricultural disease mitigation. These readily adaptable simulations allow us to tailor interfaces for capturing subtle behavioral differences while also harnessing population-wide patterns that can be useful for modeling behaviors associated with disease management and prevention. While we do not endorse moving solely to experimental gaming simulations for gathering human behavioral data, our research demonstrates how the additional context provided via simulation can capture distinct behaviors potentially missed using traditional survey methods. Moreover, experimental gaming simulations can increase salience and engagement by immersing participants in real-world dilemmas, thus providing an alternative viewpoint that may more closely approximate real world behavior, and could be used in conjunction with traditional methods to improve our understanding of human decision making processes.

Understanding how behavior in simulated gaming environments translates to real world decisions by industry professionals is an important consideration of this behavioral research. This is still an open question that we'll continue to investigate through our research agenda. Rigorous behavioral validation is challenging due to the vast number of decisions that are tested in our simulation, and by design, farmers are unlikely to have experienced these specific decisions in the real world. The flexibility of the gaming environment to gather behaviors across a multitude of possible scenarios can provide insights into risk management investment strategies that may be difficult to discern using traditional survey instruments. We are also working toward adapting our behavioral games into digital tools and interfaces that may allow industry professionals to emulate their own production system. Creating these decision support tools from our experimental game design may help us better investigate how choices in a simulated environment relate to real-world behavior. This evolution of our experimental gaming simulations into decision support applications may provide insight into the decision making process to mitigate the spread of disease.

Online survey marketplaces, like MTurk, can provide an effective and rapid medium for recruitment in behavioral research studies. We found that the distributions of risk associated with disease management were comparable between a sample of industry professionals and online recruits. We also identified aspects in which industry knowledge can differ throughout the presented risk dilemma. In particular, we found those with an industry background had a greater propensity to reduce uncertainty in the decision making process. Our study demonstrates the importance of validating simulated behaviors using a sample of participants with industry knowledge, in order to identify and account for potential differences that may be associated with their agricultural background. The similarities in general behavioral risk we've further investigated in this study also help validate our findings in Clark et al. (14), which tested hypotheses on a much larger sample ($N = 1,000$) of online recruits. Our research framework highlights the viability of online marketplaces for behavioral analysis, while also demonstrating how targeted recruitment from industry stakeholders can provide additional insights into these complex decision mechanisms.

Managing the economic factors associated with disease risk management is a complex quandary. Here we quantify behavioral aspects of the decision making under risk associated with mitigating the spread of disease while maximizing profits using experimental gaming simulations. Importantly, we found that risk preferences assigned via the paired lottery choice survey were not adequate in predicting behaviors in our simulated environment. These studied behaviors and their effect on the well-being of the system as a whole should be further investigated for the promotion of healthier agricultural production networks.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Vermont IRB # CHRBSS-16-232-IRB. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

EC contributed to conceptualization, data curation, formal analysis, software, visualization, and writing—original draft. SC contributed to conceptualization, investigation, methodology, project administration, supervision, and writing—review and editing. LT contributed to software and writing—review and editing. GB, NC, OL-C, and TS contributed to writing—review and editing. CK contributed to funding acquisition, project administration, and writing—review and editing. AZ contributed to conceptualization and writing—review and editing. JS contributed to investigation, project administration and writing—review and editing. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2020.556668/full#supplementary-material

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