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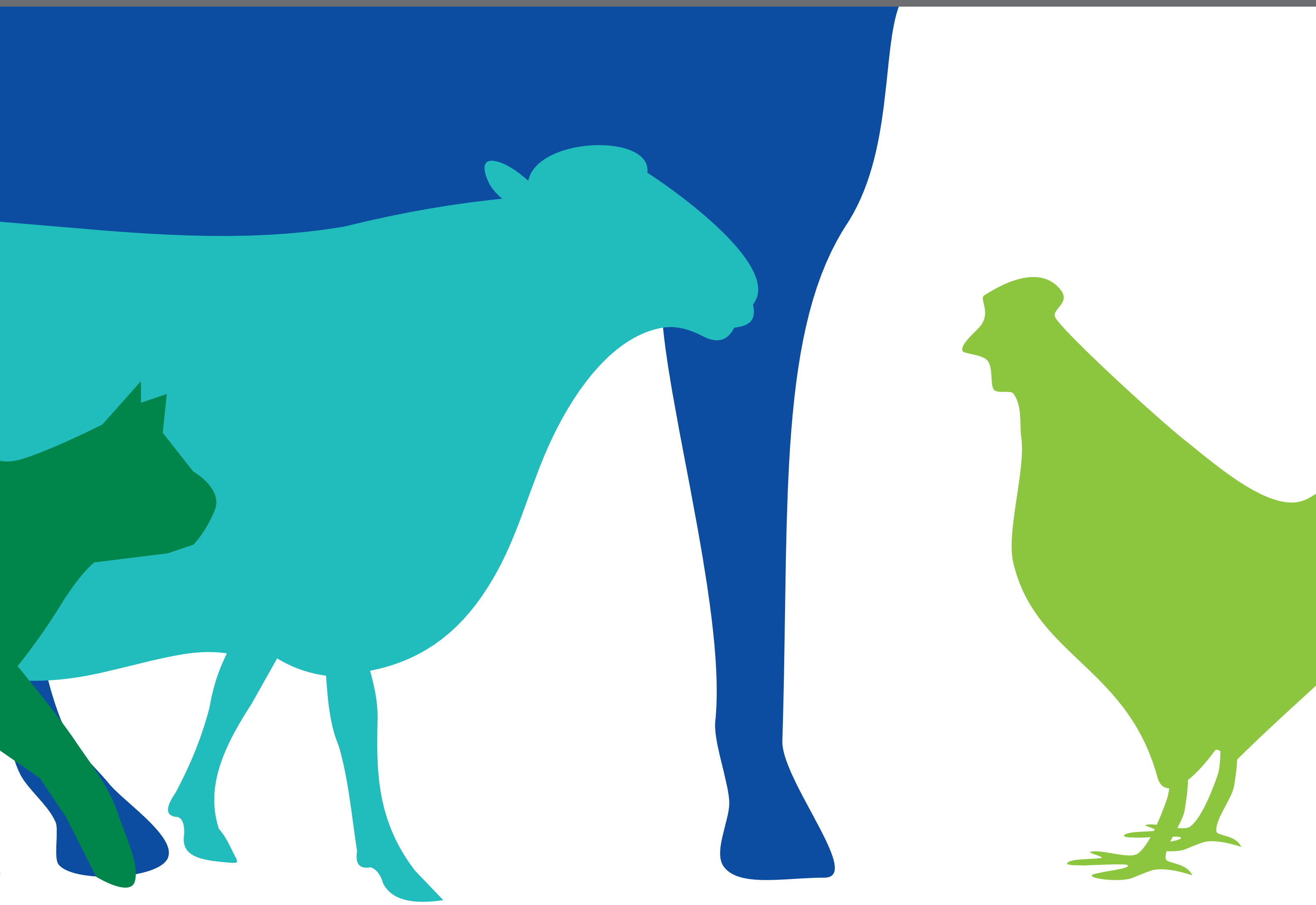

frontiers Research Topics

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PROCEEDINGS OF THE 2ND ISESSAH CONFERENCE 2018

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EDITORIAL
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Editorial: Proceedings of the 2nd ISESSAH Conference 2018

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Editorial on the Research Topic

Proceedings of the 2nd ISESSAH Conference 2018

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INTRODUCTION

Knowledge and skills in economics and social sciences are becoming increasingly significant in the animal health sector and play an important role in making sure animal health investments are people-centric (1). These skills provide a basis for decision-making processes within the livestock and animal health sectors at scales ranging from individual owners to farms, and from the livestock and food industries to regions and countries. The trend toward greater reliance on economics and social science skills reflects the complexity and variability of situations in the field, which require a whole-system approach (2)[1]. General "one size fits all" rules are not sufficient anymore; rather, insights are needed into the economic impacts of animal diseases, the profitability of potential interventions, and an understanding of the behavior of the people involved, including farmers, veterinarians, government officials, and the public. The need to take into account different views and therefore values of resources and outcomes during decision making often requires multi-criteria analysis to inform the trade-offs society faces in resource use. The optimization of societal benefits has to consider an individual's behaviors and social relationships within the disciplines of animal health management and disease control.

The International Society for Economics and Social Sciences of Animal Health (ISESSAH), established in 2017[2], held its second conference in Montpellier, France in May 2018. The Society promotes transdisciplinary research and joined with the Innovation in Animal Health International Forum[3] and the Economic Reasoning for Improved Animal Health Network[4] to ensure this was achieved at the Montpellier meeting. The proceedings of this 2nd ISESSAH conference focus on how economics and social science approaches can support decision making and governance in animal disease prevention, surveillance, and control. The aim of the conference was to highlight how the principles of economic assessment and social sciences can be applied by stakeholders and leading thinkers in the field to support animal health education, research, and policy making. The 11 papers in the proceedings reflect three themes: infectious diseases, biosecurity, and alternative methods.

[1] https://animalhealthmetrics.org/approach/
[2] http://www.isessah.com/
[3] https://www.alphavisa.com/isessah-innovsur/2018/
[4] https://epidec.weebly.com/

ECONOMIC ASSESSMENT AND DECISION ANALYSIS APPLIED TO INFECTIOUS DISEASES

Three studies highlight the usefulness of re-contextualization to improve decisions related to animal health. Montiel et al. applied the "Sustainable Livelihoods Perspective" to Mexican goat farming, demonstrating that brucellosis control offers an opportunity for small-scale goat farmers to stabilize their income and contribute to rural population welfare, ultimately reducing the likelihood of migration to the U.S. Using participatory research and interdisciplinary dialogue with Basongora pastoralists in Uganda, Chenais and Fischer highlighted how paying attention to "situated knowledge" and "embodied objectivity" improved the relevance of advice on cattle disease control. Lastly, Pramuwidyatama et al. investigated 27 measures against highly pathogenic avian influenza (HPAI) in Indonesia in 2012–2017. The animal vaccination-based HPAI mitigation strategy chosen by the government to safeguard humans from HPAI transmission had a low implementation feasibility that was attributed to insufficient collaboration among farmers.

Three other studies proposed quantitative economic evaluation to support decisions on zoonoses or national disease control programs. Thomas et al. used a food chain risk analysis model to determine the incremental cost-effectiveness ratio (ICER) of *Taenia solium* control strategies. The addition of a vaccination and treatment protocol to meat inspection (+10.3% cost) improved the ICER by 74.6%, and reduced pork industry losses from condemned meat by 66%, highlighting the potential to leverage private sector investment. Because the rationale of *Salmonella* control in pig feeds is debated, Niemi et al. carried out a cost-benefit analysis on the current Finnish control policy as compared to a reduced-control scenario. The current control policy benefits consumers, while a substantial portion of the cost is borne by feed operators; this suggests that a focus on financial responsibilities could increase acceptability of the current policy. Lastly, Gethmann et al. evaluated the German compulsory program to eradicate bovine viral diarrhea (BVD), in force since 2011, through a cost-benefit analysis between BVD control and no-control scenarios. None of the scenarios leading to complete BVD eradication was economically attractive [benefit-cost ratios (BCR) 0.64–0.94]. Only the former and the current national BVD control programs of "ear tag testing and culling" reduced BVD prevalence to 0.01%, with acceptable BCRs of 1.22 and 1.24.

ECONOMICS AND SOCIAL SCIENCES APPLIED TO BIOSECURITY

Biosecurity is a powerful tool to manage animal diseases, from enzootic production to emerging diseases. The investments are not specific to any particular disease, and good biosecurity practices form the basis for sustainable production, yet farmers often have difficulty justifying and implementing biosecurity measures. Through a systemic approach to understanding human behavior, economic modeling, and social sciences research can assist in defining multi-disease benefits from biosecurity measures and lead to strategies that improve biosecurity compliance. Four studies in the proceedings emphasize the importance of this type of research.

The core biosecurity recommendations outlined in the U.S. Secure Pork Supply Plan include written site-specific biosecurity plans that involve the implementation of a perimeter buffer area and a line of separation. Pudenz et al. showed the complexities of biosecurity measures adoption. Their results indicate that adoption is affected by how feasible producers believe implementation of each biosecurity practice is for their operation, and on the producers' perception of risk. The authors found that implementation of one biosecurity practice was likely to increase the marginal efficacy of another biosecurity practice, such that a global approach may be useful. Merrill et al. also addressed this with a "serious gaming" approach, showing that compliance in biosecurity is influenced by the method of message delivery, increased situational uncertainty, and increased risk. Similarly, Bucini et al. developed an agent-based model that combines epidemiological dynamics and heterogeneous human decisions. Scenarios applied to porcine epidemic diarrhea virus showed that relatively small shifts (10% of the producer agents) toward a risk averse position can lead to a significant decrease in total incidence of disease. Lastly, the big-five personality traits were associated with biosecurity level as expressed by a "continuous animal hygiene index" and a "technical animal hygiene index" (Döring et al.). Interactions of personality traits with biosecurity level were demonstrated, and the results depended on production systems and rating perspectives.

FOCUS ON NEW METHODS

ISESSAH promotes innovative economic and social science methods applied to animal health in order to improve animal health and welfare policies, programmes, and actions worldwide. A good example of this is the study by Barratt et al. on foot-and-mouth disease management using an innovative time series methodological framework to estimate the indirect costs of animal disease control strategies. This model takes into account how market dynamics may change following a disease outbreak, and estimates more precisely the indirect costs and wider knock-on price effects between sectors. The work by Merrill et al. and Bucini et al. are some of the first applications of "nudge theories" to animal health actors, and are based on experimental economics methods. Nudges for greater compliance with practices or that modulate risky behaviors appear to be promising approaches for animal health.

Together, the 11 papers in the 2nd ISESSAH conference proceedings provide a good overview on how different economic and social science approaches can contribute to animal health management and disease control. Complementarity among disciplines and continuous improvement in methods will support better decision making in animal health in both the short and long terms. Through the organization of annual conferences and many other initiatives, ISESSAH provides opportunities for animal health professionals to achieve wider societal benefits. Gathering our forces and competencies and focusing them on improving animal health is our organization's daily motivation.

AUTHOR CONTRIBUTIONS

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

REFERENCES

1. Rushton J. *The Economics of Animal Health and Production*. Wallingford: CABI (2009).
2. Rushton J, Bruce M, Bellet C, Torgerson P, Shaw A, Marsh T, et al. Initiation of global burden of animal diseases programme. *Lancet*. (2018) 392:538–40. doi: 10.1016/S0140-6736(18)31472-7

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ORIGINAL RESEARCH
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Increasing the Local Relevance of Epidemiological Research: Situated Knowledge of Cattle Disease Among Basongora Pastoralists in Uganda

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Cattle disease can have severe negative impacts on the livelihoods of the poor, but still, animal disease management and outreach often remain suboptimal in low-income settings. In a study on Basongora pastoralists in Uganda, we examined local priorities, perceptions and practices regarding cattle disease, in order to improve outreach and disease control advisory work in such contexts. We also investigated how participatory epidemiology can be better equipped for gathering situated knowledge. Empirical material obtained in focus group discussions, interviews, participatory mapping, and wealth-ranking was used to perform a thematic, bottom-up analysis. The concepts of situated knowledge and embodied objectivity and insights from participatory research and interdisciplinary dialogue were applied to better embrace local perspectives. Cowdriosis, trypanosomosis, contagious bovine pleuropneumonia, East Coast fever and anthrax were high-priority diseases for participants. Lack of control over the animal health situation and money invested in treatments that did not guarantee recovery were of general importance for disease prioritization. Participants' descriptions of diseases sometimes diverged from textbook definitions. Co-infections, chronic and recurring infections and lack of access to formal knowledge were identified as important factors for differences between formal and situated knowledge. Paying attention to situated knowledge and particular context-specific issues such as proximity to a national park proved to be of special relevance for local understanding and experiences with disease. Another factor was the local importance ascribed to number of cattle, rather than production levels. These factors need to be taken into consideration when formulating disease control advice, as does the complex disease landscape. The results reveal the importance of moving research and advice beyond curing "knowledge-gaps" and creating different ways of understanding disease so that situated knowledge can be considered, and disease control improved.

Keywords: participatory epidemiology, livestock, disease ranking, local knowledge, participatory research, participatory rural appraisal

INTRODUCTION

Livestock are crucial for the livelihood security of many poor people. They provide valuable protein, manure, and draft power, but also function as social status symbols and walking banks (1). The embodied effects of animal disease thus often markedly increase livelihood vulnerability (2). This study was performed with Basongora pastoralists in Isaazi village, Nyakatonzi subcounty, Kasese district, south-western Uganda (see **Figure 1**).

Due to their dependence on cattle, pastoralist livelihoods might be particularly vulnerable to the impact of bovine disease. For the same reason, pastoralists can be expected to be more knowledgeable about these diseases and their treatment than other poor communities in similar contexts. In this study we sought to consider how the Basongora in Kasese district prioritize, understand and deal with cattle disease and the related constraints they face. Our aim was to start from local perspectives and priorities, and let these guide the study. Few such studies have been performed to date in veterinary medicine and epidemiology, Examples of the exception are an early participatory epidemiological (PE) study of animal diseases in pastoralist communities in Somaliland (3), and a later study on goat diseases in Turkana South District in Kenya (4). These studies both applied local perspectives to identify diseases of importance for the studied communities.

Based on the findings from the present study, we discuss how future research might better take into account local knowledge and priorities, and what the effects of doing so were in the present study. We also suggest some ways of making epidemiological research more fully embrace local perspectives and practices, and thus provide research findings of increased local relevance. Finally, we suggest some practical measures for improving outreach and adoption of disease management in these contexts.

Researching Situated Knowledge of Cattle Disease

The importance of researchers and policy makers acknowledging that all knowledge is situated, and not simply regarding local ways of knowing and prioritizing as inferior, has been repeatedly emphasized [e.g., (5, 6)]. However, recent research shows how acknowledging other forms of knowing than formal "textbook" knowledge has arrived later in veterinary medicine than in many other academic disciplines, and that such acknowledgement can have significant positive effects on the dialogue between veterinarians and farmers (7). For example, applying very detailed knowledge about a disease and associated recommendations about its treatment produced by veterinary researchers without local engagement, might not be wrong *per se*. However, such approaches will likely produce knowledge that is not well anchored in the local situation and does not accurately acknowledge complex disease ecologies and economic constraints limiting treatment possibilities. Such decontextualized knowledge will be difficult for local people to act on (7).

We argue here, that if veterinary research and practice take the approach to knowledge not as an object to be gained or not, but as something situated and locally specific, it will be better equipped to understand local accounts of disease, including how and why they might differ from textbook descriptions. Such acknowledgement would facilitate both research and practical veterinary work [see (7) for a similar reasoning]. One of the early writers on this is Haraway (8), who describes how modern science has colonized "objectivity" as detached from context, and universally applicable. By slicing up reality and dividing responsibility for understanding the world into different disciplines, very detailed and seemingly "objective," but highly decontextualized and selective, accounts of the world are created. Haraway (8) points out that these accounts of the world, like any other knowledge, are partial and situated but claim to be general, thereby particularly excluding knowledge and realities of marginalized groups in society. The term "embodied objectivity" reflects the fact that objectivity is never detached and neutral, but must be judged in its context [see also e.g., (5, 6)].

One strategy for facilitating this openness to different ways of knowing has been to engage in interdisciplinary dialogue (9, 10) and to employ participatory methods (6, 11). Participatory methods aim at making policy and research more sensitive to local conditions (12). By doing so it can have a significant impact in attuning development work and research to poor people's realities (13). In this way participatory methods can also facilitate that implementation of research findings and policy interventions are grounded in priorities and needs of the local people. PE in veterinary science has been developed as a tool for collecting epidemiological data in contexts where conventional quantitative data are unavailable. However, recent research has shown that the focus on being accepted by the conventional veterinary research community has led to "participation" in PE, and the resulting relevance of the findings to local people, being rather limited (14). In this study, we as authors combined our expertise in veterinary medicine and rural development studies, respectively, while remaining equally open to local competence, drawing on participatory methods.

MATERIALS AND METHODS

Data collection was designed to embrace local perspectives on cattle disease. We performed focus group discussions (FGDs), individual interviews, participatory wealth-ranking and mapping. Participants were selected on the basis of purposive sampling strategies (15). All interviews were guided by a pre-defined topic guide outlining broad topic areas, while remaining open to inclusion of additional topics by participants. Before implementation of the study the local research team, consisting of facilitator, note-taker (both veterinarians) and an interpreter, jointly translated the interview topic guide from English to Lutoro/Rusongora. A pilot FGD was conducted to test the set-up and the local relevance of the questions. The participants in the pilot FGD were from a village neighboring the study village and recruited in the same way, with the same requirements and procedures, as for FGDs included in the study. Results from the pilot FGD were not included in the results. The topic guide can be found as Supplementary Material 1.

FIGURE 1 | The study village, marked as a dot on the map, is located in the western part of the "cattle corridor" stretching through Uganda in a north-westerly direction.

Data Collection

Following the pilot, eight FGDs, four with women and four with men, were performed. These groups were convened by a key informant working for a local non-governmental organization in the study village and residing in an adjacent village. The requirements for participation in FGDs were that participants lived in the study village, were over 18 years and owned or tended cattle. Groups of at most nine participants were organized and each new group consisted of people who had not previously participated.

In the beginning of each interview and FGD the research team informed about the study and its objectives, especially pointing out that it was a research project and not a need assessment or similar, with possible immediate benefits for the community. All respondents were asked for their oral or written consent (including for audio recordings and photos) and informed that they could refuse to answer questions and withdraw from the group at any time. The facilitator followed the topic guide while being sensitive to participants' wishes to express concerns and comments outside this frame, and ensured that the discussion was not dominated by one or a few individuals. The authors intervened and gave feed-back if deemed necessary. All participants spoke Rusongora, while the interpreter and the facilitator spoke Lutoro. Lutoro and Rusongora are sufficiently similar for translation to work smoothly, but inevitably some detail may have been lost. Detailed notes were taken throughout the field work. The discussion was simultaneously translated to English and the translation recorded on audio-tape for back-up, but not transcribed verbatim. Notes taken by the note-taker and both authors, as well as the audio-tape recordings, were frequently compared and discussed with the research team and key informants. Quotes used in this paper should not be seen as exact translations, but as illustrations intended to give life to the findings.

Participatory mapping (16) of the village depicting all households was conducted (see **Figure 2**). The group performing

FIGURE 2 | Map of the study village indicating all households and their wealth rank. Households are numbered 1–199 in plain numerals. Wealth rank is indicated as 1–5 in encircled numbers. Households marked √ participated in the first eight FGDs.

the participatory map and wealth ranking consisted of five men identified by the key informant for their knowledge of the village and of all households. They had not participated in the FGDs. The participatory mapping improved the research team's understanding of the local geography, helped identify geographical areas of the village covered in initial focus groups and was used as a basis for subsequent wealth ranking. The wealth ranking, designed with inspiration from Jacobson (16), aimed at capturing local perspectives on poverty and wealth and identifying the relative wealth of each household using the participatory map. There was significant agreement in the group about factors deciding wealth rank. These were:

- Education of children.
- Private ownership of land.
- Number of cattle.
- Household monetary income.
- Quality of dwelling house.

Based on these factors, participants agreed on five different wealth ranks, which were subsequently cross-checked in a FGD with five women. This revealed substantial correlation between the factors prioritized and the overall importance of cattle, but the women added the importance of wife and children being well fed.

The mapping indicated that 70 out of a total of 199 households participated in the initial eight FGDs. There was no notable difference in the distribution of wealth ranks of the households participating and not participating in the initial eight FGD groups. However, one geographical area where many widowed or divorced women live emerged as under-represented in the initial eight focus groups. We therefore conducted one more FGD with five women from this area of the village. The participants for this FGD were recruited with the same instruction as for the initial eight FGDs, but restricted to women living in the indicated area. This FGD also served the purpose of cross-checking the factors deciding the wealth rank, as described above. We also conducted one additional FGD with seven (male) cattle care herders owning few or no own cattle, and four additional interviews with seven young men herding other people's cattle, as we suspected that the perspectives of this group might not have emerged in the FGDs. The herders were encountered and approached while the researchers walked around the study village and recruited for an immediate FGD or interview. This approach was selected as it was difficult to make herders leave their duties and take part in a scheduled FGD. However, the FGD and interviews with herders did not indicate that these participants had different knowledge and experience of cattle disease than cattle owners.

With the overarching research question as a guide, we conducted a thematic, bottom-up analysis where we let the empirical data guide the categories emerging. In both data collection and analysis, we aimed at preserving the diversity of perspectives emerging, rather than forcing consensus. Literature on the local social and ecological conditions affecting Basongora livestock keepers, and of the diseases and vectors mentioned by interviewees, facilitated analysis of the local empirical material and provided grounds for dialogue between local and non-local knowledge on cattle production and disease.

RESULTS

Cattle disease was a topic that prompted significant engagement in the interviews, indicating the significant of cattle in the Basongora culture. Number of cattle owned was central for perceived status and wealth in the community, and even households ranked among the poorest still had a few cattle, indicating the priority given to investing in cattle. However, similarly to many other traditional cattle-based communities (17), it was the number of cattle that was important and production levels were not prioritized. Cattle were frequently kept to old age (up to 16 years) and cows were described to produce up to 15 calves in their lifetime. Cows were further described to calve the first time at 6 years of age and producing approximately 2–3 L of milk per day during the lactation period.

Situated Knowledge of Cattle Disease in the Study Village

During the FGDs, participants were asked to list all diseases they had observed in their cattle in the past 2 years. The limit of 2 years was set to give a period sufficiently near in time for participants to remember and sufficiently long to capture a wider range of diseases of relevance. However, we did not relate this time span to any other specific events in the community that could have helped the participants define it more exactly, and thus it should be taken as a rough indicator. A total of 38 different cattle diseases, syndromes, signs or external parasites were mentioned (**Table 1**). The fact that many of these are not diseases in a formal sense indicates the broader perception of disease in the community, the general lack of a strong link between formal and informal veterinary knowledge and lack of access to veterinary services. Since 1999, every sub-county in Uganda is expected to have a government-employed veterinarian. Kasese district is divided into 23 rural sub-counties and six town councils/divisions (18, 19). While Nyakatonzi is one of the sub-counties that have employed a veterinarian, this veterinarian does not live in Isaazi village. However, a private veterinarian is residing in Isaazi. Local estimates and our own calculations based on wealth ranking indicate that Isaazi villagers own 8,000–10,000 cattle, excluding calves. Since Isaazi is one of 11 villages in Nyakatonzi sub-county, the total number of cattle clearly exceeds the amount that one or two veterinarians could handle. Thus, participants to a large extent have to manage disease and other production challenges without consulting animal health professionals. Of the 38 diseases mentioned, 12 were described as being the most important in one or more FGDs and five (cowdriosis, trypanosomosis, contagious bovine pleuropneumonia (CBPP), East Coast fever (ECF) and anthrax) were mentioned particularly frequently (**Table 2**). There was no obvious difference in interview responses between women or men, or between cattle owners and herders, regarding the diseases mentioned or their prioritization. Below we provide brief textbook-type descriptions of these five diseases, followed by their Rusongora names, local descriptions, including their signs and causes, and participants' stated reasons for rating a particular disease as most important.

TABLE 1 | Exhaustive list of all cattle diseases, syndromes, signs or external parasites mentioned in focus group discussions (FGDs).

Disease*	Number of FGDs mentioning the disease*
Anthrax, cowdriosis, East Coast fever (ECF), trypanosomosis	10 (=all)
Contagious bovine pleuropneumonia (CBPP)	9
Foot and mouth disease, worms	8
Fever, lumpy skin disease	7
Ephemeral fever	6
Anaplasmosis, tuberculosis	5
Diarrhoea, tetanus	4
Eye-worms	3
Cough, brucellosis, pink eye, tick fever	2
Abscesses, bloody diarrhoea, constant urinating, constipation, fever and cow goes blind, head shaking, high fever and dry faces during dry spell, laminitis, mastitis, papillomatosis, photosensitivity, rhinderpest, ring womb, ring worm, small elephant flies, standing hair coat, still births, ticks, unknown disease: rotten intestines at slaughter	1

Disease (including diseases, syndromes, signs or external parasites) names are those given by the participants, directly translated into English.

TABLE 2 | Diseases, syndromes, signs or external parasites ranked among the top five most important in at least one focus group discussion (FGD).

Disease*	Number of FGDs where the disease* was ranked top five
Cowdriosis, trypanosomosis	9
Contagious bovine pleuropneumonia (CBPP)	8
East Coast Fever (ECF)	6
Anthrax	5
Diarrhoea, fever, tick fever, worms	2
Cough, bloody diarrhoea, eye-worms	1

Disease (including diseases, syndromes, signs or external parasites) names are those given by the participants, directly translated into English.

Cowdriosis

Cowdriosis, or heartwater, is caused by the bacteria *Ehrlichia ruminantium* and is spread by Bont ticks (*Amblyomma* spp.) (20). The disease is endemic in many parts of Africa and causes fever, nervous signs, diarrhoa and ultimately death (21). The Rusongora name for cowdriosis is *omutwe*, literally meaning headache. All FGD participants described the signs of cowdriosis as cattle getting a stiff neck or head leaning to one side and the animal starting to move in circles, isolating itself and turning mad. Many other, less specific, signs of the disease were also mentioned, and it was pointed out repeatedly that it was difficult to diagnose the disease in time to enable successful treatment.

Although all FGDs identified cowdriosis as a tick-borne disease, tsetse flies (*Glossinia* spp.) and small elephant flies (*Tabanidae* spp.) were also mentioned as disease vectors. Other factors mentioned as causing the disease were prolonged drought and lack of feed, animals being struck too hard by the herder or animals fighting with other animals. Lack of access to veterinary services, not applying acaricides according to recommendations and treatment failure of acaricides were also mentioned as reasons for the disease. Cowdriosis was regarded as important because it is common and causes (sudden) death. Both preventive and curative measures were mentioned as being ineffective and expensive. The clinical signs from the central nervous system were mentioned as both dangerous to manage and economically damaging, as infected cattle stray and get lost, preventing sale or consumption of the meat. Infected wild animals and vectors from the nearby national park were mentioned as complicating control of the disease.

Trypanosomosis

In East Africa, trypanosomosis in cattle is generally caused by *Trypanosoma brucei brucei*, *T. congolense* or *T. vivax,* and is transmitted by tsetse flies (*Glossinia* spp.). Infection can cause various signs such as lymphadenopathy, anemia, anorexia and death (22). Signs can present along a range from acute to chronic (21). The Rusongora name for trypanosomosis is *ekipumpuru*, which translates directly as emaciation.

The signs of trypanosomosis mentioned in the FGDs were many and varied. Many related to production losses, such as milk drop, giving birth to weak calves and abortion, but also e.g., diarrhoa, standing hair coat, lack of appetite, weight loss, eye problems and swelling around the neck. Some participants also mentioned that the signs are vague and that the disease weakens the immune system, which might mean that simultaneous infections make it particularly difficult to diagnose the disease.

Seven out of 10 FGDs mentioned tsetse flies as causing trypanosomosis, but six FGD also mentioned ticks as insect vectors. Many participants further emphasized the role of elephants (from the national park) in disease transmission. Elephants kicking the soil and making holes where water collected and cattle drinking together with elephants were mentioned as causing disease transmission. Hunger, limited pasture, and prolonged drought were also mentioned as causing the disease. Some FGD participants associated increased incidence during drought with a disease-causing agent in the soil.

Trypanosomosis was regarded as important because it causes death, particularly in calves. It was also mentioned that this disease often recurs after treatment. Economic impact related to impaired production, failed reproduction, difficulties in selling infected animals and costly treatment were also frequently mentioned. The difficulties in selling infected cattle were specifically related to the impaired body condition, probably further reflected in the Rusongora name for the disease. Ticks, tsetse flites and vertebrate vectors from the national park were mentioned as complicating factors in controlling the disease.

Contagious Bovine Pleuropneumonia (CBPP)

Contagious bovine pleuropneumonia is covered by animal health laws in Uganda and its control is under governmental responsibility (23). It is caused by *Mycoplasma mycoides* subsp. *mycoides* and causes a very serious and contagious respiratory disease (21). The Rusongora name for CBPP is *kihaha*, which is closely related to the word for lungs (*ekihaha*). CBPP was particularly described as causing cough. Other signs mentioned were discharge from nose and eyes, lethargy, loss of weight, diarrhoa, standing hair coat, fever, abortions, and milk drop. Several post-mortem signs were also mentioned (particularly by the men, as women do not participate in slaughter) including damaged lungs and the lungs being attached to ribs and to other organs.

Many participants mentioned that CBPP can spread through infected cows entering a herd or passing nearby. Transmission occurring through wildlife (from the national park), and through humans who had stepped in infected cow dung was also mentioned. However, the particular pathogen was not known by the participants.

CBPP was regarded important because it is common, causes many deaths, is easily transmitted and requires treatment that is not available locally. Economic impacts arise from loss of value of cattle, and from trade restrictions due to quarantine ("*quarantine causes loss of income because you cannot sell milk or sell cattle that is needed to pay for school fees*"). The post-mortem signs also reduce the value of the meat and cause fear of zoonotic disease transmission, probably as a result of the damage the disease causes to internal organs (although it can be noted that in fact the disease is not zoonotic).

East Coast Fever (ECF)

East Coast fever is caused by the parasite *Theileria parvum* spread by the brown ear tick (*Ripicephalus appendiculatus*) (20). It is endemic in east Africa, often causing fever, enlarged lymph nodes, dyspnoea, wasting, and diarrhoa, followed by death (21). The Rusongora name for ECF is *omuswija*, which translates as high fever.

Like trypanosomosis, ECF was described with a variety of symptoms. Many participants said that it was more common in calves, or even that it only occurred in calves. Signs of disease mentioned included fever, swollen lymph nodes, nasal discharge, and swollen eyes, standing hair coat, cough, labored respiration, diarrhoa, inability to stand up and anorexia.

Only five out of 10 FGDs said that ECF was caused by ticks. Some also mentioned flies in general, and tsetse flies in particular, as disease vectors. Dry spells and too much wind and sunshine were also mentioned as causing the disease. Calves drinking too much milk or irregular milking (i.e., irregular milk availability for calves) were repeatedly mentioned as factors causing the disease. Some also said that the disease could spread by milking infected cows. ECF was regarded as important by participants because it is common and causes death, especially in calves ("*Calves are cows of tomorrow, if calves die that is bad*"). Sudden appearance, difficulties in diagnosis and the need for treatment to avoid a fatal outcome were also mentioned, as was fear of zoonotic infection potential via milk ("*If you take the milk from a cow with fever also the humans get sick, but you cannot stop taking milk, it is the delicacy*").

Anthrax

Anthrax is a fatal disease in cattle, often presenting with per-acute death. It is caused by spore-producing bacteria *Bacillus anthracis*, the spores of which can survive in soil for a very long time. The spores are often unearthed in extreme weather conditions such as droughts or floods, or a combination of these (21). The Rusongora name for anthrax is *kakooto*. The etymological background to this name could not be clarified, but it is possibly related to the word for "enlarged."

Anthrax was particularly described by its sudden appearance. Many said that there were no signs before death, while others mentioned swelling of the body and bleeding from nose and anus before or just after death. In particular, men also reported several post-mortem signs, including the meat looking "*as if it were boiled*," enlarged spleen, no rigor mortis, watery blood and blood coming out of body orifices.

Many participants mentioned that anthrax comes from the soil, especially during droughts. Those who did not identify the soil as the disease source were still aware that anthrax appears especially during droughts, and that it comes somewhere from the pasture. It was well known that meat from infected cattle is a danger to public health. Anthrax was regarded as important because of its deadly outcome, the sudden onset ("*Anthrax can attack without noticing, you only realize as blood is oozing out of mouth and anus*") and by affecting seemingly healthy cattle. The zoonotic potential and the economic impact from not being able to consume or sell the meat were also mentioned.

Local Priorities of Cattle Disease

As seen in the sections above, many of the reasons given for the relative importance of particular diseases were general, and more related to the participants' situation and the context than to the specific diseases. Such more general aspects are described below.

The aspects of the diseases that influenced perceptions of their relative importance can be grouped into themes relating to: epidemiological parameters and expected final outcome of the disease, prospects for success of available treatment, economic impact, clinical signs, causes of the diseases, the national park, acaricides, and uncertain elements (i.e., if the cause, diagnosis or treatment was unknown to the participants). In more detail, and using epidemiological terms, the first theme relating to the relative importance of a disease could be described as disease incidence, prevalence, contagiousness, hereditary potential, and case fatality rate. Aspects of the outcome of disease, notably death or a chronic/progressive disease course, added to the relative importance of a disease. A disease appearing suddenly or death occurring without previous signs were factors contributing to the relative importance. Such aspects make diseases difficult to prevent or control and add to livelihood vulnerability. For similar reasons, the expected success of treatment, if a disease recurs after treatment, if the treatment does not cure the disease and if the animal dies even when treated were repeatedly emphasized. In this regard the availability of drugs and the problem with inefficient acaricide treatments were frequently raised. Economic impact (e.g., cost of treatment, possibility to sell the meat, market value of cattle, zoonotic potential hindering consumption and trade, and diseases imposing quarantine measures preventing trade of cattle and their products) were also mentioned as important. However, economic impact went well beyond monetary value at point of sale and could be described in terms of: (1) Maintaining the herd (rather than e.g., being able to sell animals) and (2) spending money on ineffective treatment. Again, underlining the value of herd size, disease in calves was often mentioned as particularly devastating owing to their value as future replacements for cows. With regard to ineffective treatment, in particular the problem with ineffective or "fake" acaricides on the market was repeatedly stressed, also when talking about diseases that are not tick-borne ("*acaricides are ineffective even if we spray twice weekly,*" "*we lost a lot of money because the acaricides did not kill the ticks*").

Local Disease Management

Participants reported that they often did not consult animal health professionals but treated their cattle themselves or sought help from other community members. This was especially mentioned as being the practice for the more common diseases such as cowdriosis, trypanosomosis, ECF, parasites, fever, and diarrhoa. In these cases, therapeutic drugs were obtained from the local market, drug shop or agriculture input provider. Furthermore, the long tradition, culture and experience of cattle keeping in this community were mentioned as providing a base of knowledge about treating cattle diseases. One of the key informants explained that everyone in the village had significant knowledge about cattle production, different diseases, and their treatment, "*but what differs between people is the possibilities to do something about the disease.*"

Some traditional treatments options were mentioned, such as using particular plant extracts for treating cowdriosis and trypanosomosis. At the same time, local treatments seemed overall to have significantly declined with the introduction of formal medicines, even when these did not function satisfactorily. For example, despite the very frequent complaints about ineffective acaricides, other means of controlling ticks, such as hand-picking or smearing plant extracts, urine or waste oil, were mentioned as not being in use anymore.

Many participants mentioned that they would contact the local village veterinarian, or the government veterinarian, if their own treatment did not succeed, for diseases they did not recognize or for some specific diseases (CBPP, foot, and mouth disease, anthrax, lumpy skin disease). However, despite Nyakatonzi being one of the sub-counties in Kasese district that have a government veterinarian employed, and despite a private veterinarian residing in the village, many villagers reported difficulties in accessing veterinary healthcare. Apart from lack of access, avoiding costs for paying the veterinarian was mentioned as a reason for treating cattle themselves or asking other community members for help before consulting animal health professionals. As the veterinarian was often called out only after local attempts at treatment had failed, the success rate of veterinary treatments is also likely to be low.

DISCUSSION

The results and available literature indicate several reasons for diversions between textbook and local disease descriptions. These include co-infections, chronic, intermittent and recurring infections and lack of local knowledge on disease-causing agents, leading to local understanding, and classification of diseases focusing on clinical signs. As an example, the clinical signs used to describe trypanosomosis were especially varied. In a study by Catley et al. (24), agro-pastoralists in Sudan described trypanosomosis as a chronic wasting disease, leading those authors to conclude that the varied signs described might reflect co-infections with several endemic diseases, as might also be the case in our study. Another explanation for the varied, and somewhat vague, descriptions of clinical signs might be that the cattle suffer from more or less constant under-nourishment (25), leading to a general weakened immune response, making differential diagnosis difficult. Although not discussed as such by the participants, we for example interpret the local accounts regarding cattle reproduction and milk production as harsh ecological conditions and disease pressure causing significant constrains on productivity.

In a study of local knowledge on tick-borne diseases (TBDs) in cattle among Karamoja pastoralists in Uganda, participants described co-infections with several TBDs such as anaplasmosis and ECF, leading to the conclusion that such co-infections might lead to under-estimation of the true prevalence of disease (26). Co-infections also affect disease management and the local relevance of disease control advice. Participants in our study frequently discussed treatment failure of acaricides as a reason for failed prophylaxis of trypanosomosis, despite the insect vector being tsetse flies, not ticks (22). Both single and combination preparations (effective against ticks and tsetse flies) were used in the study village, but this difference in vectoricid-range was never mentioned by participants. Rather than interpreting this as local misrecognition of the disease-causing agent, we concluded that if cattle are concurrently exposed to tsetse flies carrying *Trypanosoma* spp. and several species of ticks (20) carrying one or several TBDs, a sub-clinical infection by any TBD might exhaust the animal's immune system, making it succumb to clinical trypanosomosis. The local emphasis on acaricides for treating non-TBDs might also reflect a general wish to have access to better disease treatments. In the same way, the local connection made between trypanosomosis, reproductive failure and abortions might be caused by local failures to distinguish between trypanosomosis and diseases more commonly associated with signs from reproduction system such as brucellosis, or by co-infections making the signs less obvious. Brucellosis was only mentioned in two out of ten FGDs, and never mentioned as an important disease. In recent findings from the same area by Wolff et al. (27) the prevalence of brucellosis was high (40%).

Another example of how a broad exploration of situated knowledge of animal disease could contribute to more robust research findings on local disease-related challenges and assist in potential identification of new diseases was the case of "fever." Participants described three different syndromes of "fever": fever, tick-borne fever and ECF. While ECF was acknowledged locally as an important disease, the descriptions often did not comply with the textbook description. It was described as tick-borne in only half of all mentions and was frequently discussed as particularly affecting, and being more serious in, calves. However, under endemic conditions, young animals are at least partly protected by maternal antibodies and calves are thus often described as being less prone to clinical disease (28). The accounts in our study included high neonatal death rate, diarrhoa and overall high case fatality rate in calves. This led us to conclude that the disease described as ECF in calves might actually be another disease. Methodologically, it must be noted that we failed to be sufficiently thorough when discussing with the local research team about how to translate the diseases and to allow for an openness about that there might not be a one to one relationship between local and formal, as well as Rusongora/Lutoro/English disease names and meanings.

During FGDs we noted a tendency for the facilitator to force participants' descriptions of syndromes into scientifically accepted disease nomenclature that could have caused misclassification. More thorough preparation and discussions with facilitator and translator about local names and meanings of different diseases could have avoided this. As ECF in Rusongora is translated as high fever, it is likely that this term groups together several reasons for high fever, and thus that some of what was reported to us as ECF might in fact have been a different form of high fever in cattle. Two FGDs prioritized "diarrhoa in calves" as one of the five most important diseases. In these two groups, the syndrome was discussed at length and seemed to have had very negative impacts for the participants. The syndrome translated as "ECF in calves" might equally have been translated as "high fever in calves" and might actually be the same disease as "diarrhoa in calves." These two accounts of a disease new to the study community that presents with high case fatality rate in young calves can be triangulated with recent findings reporting high prevalence of bovine viral diarrhoa virus in the same area (27). It can be noted here that if our study had only been about one disease, e.g., ECF, our conclusion regarding the local reports on ECF might instead be only that there is a lack of knowledge on ECF in the study village. Acknowledging the possibility of several diseases and symptoms being incorporated within the formal name of one single disease, rather than just interpreting local inconsistencies in the characterization of ECF requires openness to different ways of understanding and classifying disease and to the possibilities of reasons other than lack of knowledge behind these local accounts.

Lessons for Disease Treatment and Advice

As noted in almost all local disease descriptions, wildlife from the nearby national park was perceived as a significant local problem for disease management; one that the pastoralists also felt that they had limited influence over. The Basongora in Kasese are together with the Karamojong to the north among few pastoral groups who still practice communal grazing in Uganda. However, their grazing land has shrunk over time due to continued competition for land from neighboring farming communities, national parks, and commercial cotton production (29). With the establishment of Queen Elizabeth National Park in 1954, which Isaazi borders, villagers lost a significant part of their grazing lands. The park still causes ongoing conflicts between pastoralists and wildlife, as mentioned frequently in interviews and confirmed by other studies in the area (30, 31). The frequency of the complaints about the national park in our interviews are clearly in part strongly influenced by the ongoing land-use tensions, which was also reflected in the wish for private ownership of land, described as a solution for secure grazing and limiting disease transmission between herds. While private ownership of land of enough size to secure own grazing will probably never be achieved, this wish also reflects a desire to have more control over the entire animal health situation. Indeed, in discussions on key challenges in disease prevention and treatment, the experienced lack of control over disease cause, prevention and treatment was evident in several ways, as was the frustration that money invested in treatment did not guarantee recovery. Given the significant livelihood vulnerability caused by animal disease and the perceived lack of control over the disease situation, local suggestions for improving animal health focused to a large extent on structural investments by the government to reduce local vulnerability (e.g., building a dip tank, vaccination, fencing the national park, providing veterinary services, and drugs). These suggestions are largely in agreement with those by Coffin et al. (31) and Byaruhanga et al. (26) for other parts of Uganda. Our study also showed common community willingness to participate and sustain infrastructures for disease control. Local residents had for example formed a producer group to restore the local dip tank. The local emphasis on the need for structural support, while at the same time seemingly not complying with some of the existing veterinary advice, can be interpreted such as that this advice were not easily adopted under local circumstances, and that structural support was judged locally to have the potential for more significant impact [see also (16, 32)]. In the present study there were examples where local tradition and livelihood constraints clearly made it difficult to act in ways that would reduce disease transmission, even if the knowledge about how to do it was there. The problems with disease transmissions from the national park is one such example. Also, there was widespread recognition among participants in this study of milk as a disease-transmitting agent but, despite this, there was evidence that recommended withdrawal times for milk during disease and treatments were not followed, because milk is an important income and an appreciated delicacy.

Some of the local lack of control over the disease situation could also clearly be reduced with more access to information of disease prevention and treatment. Like pastoralists in other parts of Africa (4), participants in this study in most cases treated sick cattle themselves, without consulting a veterinarian. The Basongora have a long tradition of keeping cattle and associated knowledge of signs of diseases. At the same time, as indicated above, local knowledge of disease-causing agents and associated evidence-based treatment is often limited, and co-infections and generally low health status of animals further complicate diagnosis and treatment. There was a strong desire amongst many participants to learn more about on how to control and treat diseases. One example of this was the frustration with the local lack of solution, and wish for us to have an answer, to the problem with diarrhoa in calves. The local importance of cattle for providing protection against vulnerability and calves as the future economic security clearly made this a pressing problem.

In general, participants repeatedly emphasized the importance of us reporting back our findings to them and asked us many questions about correct ways of treating diseases. As discussed in the final section, the results high-light the importance of such information being given in ways that makes local sense and is possible to act on.

Methodological Lessons for Making Epidemiological Research and Practice More Attuned to Local People's Realities

Despite the complex disease landscapes in many low-income countries, few studies discuss co-infections and related implications for animal health, disease control and poverty reduction. Furthermore, even with increased acknowledgement within epidemiological research of local disease prioritizations, especially through the growing field of PE (33), studies frequently remain focused on single diseases. Demands by funding bodies and the wider research culture for concrete and timely deliverables are important reasons why many studies have a pre-set and often rather narrow focus. In some cases, participatory methodologies are used as a first "scoping" stage, to set more detailed priorities for further research or development activities (4, 34, 35). Other studies focus on singling out "the most important disease in the studied community," signifying a compartmentalistic view of animal management and health grounded in an illusion of a healthy animal being struck by a solitary disease event (36). The reality, according to our findings and those of others (37), is rather the opposite: co-infections, sub-clinical disease and diseases recurring due to therapy failure. Consequently, factors contributing to the relative importance of specific diseases were in many cases not disease-specific, but general. Moreover, when participants seemingly talked about a specific disease, it was apparent that they were frequently describing situations with co-infections. Accepting this complex disease landscape has implications not only for the questions we ask while doing research, but also for the answers we give in the form of outreach and advisory services. Consequently, finding all the scientifically relevant answers regarding single diseases might not have the highest priority for communities. Instead, more general actions that can address the over-arching health status of the herd and thus prevent sub-clinically infected individuals from succumbing to clinical disease might be more relevant. This might include improving biosecurity and feeding as well as other preventive measures such as immunization and acaricide or ecto/endo-parasite treatments.

In addition, as revealed by our investigation into the meaning of local disease names, local classifications of diseases are likely to differ somewhat from textbook definitions, as exemplified by ECF locally meaning "high fever," which is likely to include ECF and other diseases causing high fever. Conventionally, triangulation is the recommended method for cross-checking local accounts of disease (33). This involves both cross-checking local descriptions of disease syndromes with key informants, and biological sampling to arrive at scientific disease names. While such approach is important for ensuring that one actually collects medical data and oral statements on the disease intended, it does not necessarily allow for an openness to local knowledge and classifications of diseases that do not fit neatly with formal scientific classifications. In this study we could have been more thorough in the preparatory work with the local research team to allow for such openness. The facilitator and note-taker in the present study were both veterinarians. This facilitated the translation of animal health terms and disease names from Lutoro/Rusongora to English, and was a valuable contribution to the triangulation process involving participants' account and official disease reporting. However, it could also have introduced a "professional filter" to what part of the discussion was conveyed and what diseases were noted down. Our results in this regard highlight the importance of continuous intense dialogue with facilitators and interpreters, preventing coercion of local accounts of disease into known nomenclature, and to the value of an open research focus in order to fully comprehend situated knowledge.

The obvious local need and wish for more information on how to deal with animal disease must be addressed. Like Coffin et al. (31), we emphasize the importance of studies claiming to be participatory taking the time to report results back to participating villagers in locally relevant ways. Several participants in this study expressed frustration about having been part of past research projects on cattle diseases and never being told the results. The present study is part of a larger research project studying tick-borne diseases on cattle in Uganda (Swedish Research Council Dnr 2016-05705). As part of this project we will report back the joint findings from the project during 2019. Our study can be used to emphasize the importance of information being locally appropriate, given in forms that makes sense in local terminologies, and that can result in concrete actions possible to implement.

STATEMENT OF ANIMAL RIGHTS AND RESEARCH ETHICS

Data was collected from interviews, observation and participatory actives in the study village. All respondents were asked for their oral or written consent and informed that they could refuse to answer questions and withdraw from the interview at any time. All individuals are anonymized.

Ethical clearance for the study was approved by Uganda National Council for Science and Technology (ref A580) and Makerere University School of Veterinary medicine and Animal Resources Research Ethics Committee (SVARREC 03/2017).

AUTHOR CONTRIBUTIONS

EC and KF contributed equally to all parts of the study (study design, construction of the interview topic guides, fieldwork, data analysis, drafting and writing 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.2018.00119/full#supplementary-material

REFERENCES

1. Otte J, Costales A, Dijkman J, Pica-Ciamarra U, Robinson T, Ahuja V, et al. Livestock sector development for poverty reduction: an economic and policy perspective. Livestock's many virtues. In: Otte J, Costales A, Dijkman J, Pica-Ciamarra U, Robinson T, Ahuja V, Ly C, Roland-Holst D, editors. *Pro-Poor Livestock Policy Initiative. A Living from Livestock.* Rome: Food and Agriculture Orgnaization of the United Nations (2012). p. 37.
2. Randolph TF, Schelling E, Grace D, Nicholson CF, Leroy JL, Cole DC, et al. Invited review: Role of livestock in human nutrition and health for poverty reduction in developing countries. *J Anim Sci* (2007) **85**:2788–800. doi: 10.2527/jas.2007-0467
3. Catley AP, Mohammed AA. The use of livestock-disease scoring by a primary animal-health project in Somaliland. *Prev Vet Med.* (1996) **28**:175–86.
4. Bett B, Jost C, Allport R, Mariner J. Using participatory epidemiological techniques to estimate the relative incidence and impact on livelihoods of livestock diseases amongst nomadic pastoralists in Turkana South District, Kenya. *Prev Vet Med* (2009) **90**:194–203. doi: 10.1016/j.prevetmed.2009.05.001
5. Davidson-Hunt IJ, Michael O'Flaherty R. Researchers, indigenous peoples, and place-based learning communities. *Soc Nat Resour.* (2007) **20**:291–305. doi: 10.1080/08941920601161312.
6. Anderson JF, Pakula B, Smye V, Peters V, Schroeder L. Strengthening Aboriginal health through a place-based learning community. *Int J Indigen Health* (2011) **7**:42. doi: 10.18357/ijih71201112352
7. Hamilton L. Bridging the divide between theory and practice: taking a co-productive approach to vet-farmer relationships. *Food Ethics* (2017) **1**:221–33. doi: 10.1007/s41055-017-0011-7
8. Haraway D. Situated knowledges: the science question in feminism and the privilege of partial perspective. *Feminist Stud.* (1988) **14**:575–99.
9. Scholz RW, Lang DJ, Wiek A, Walter AI, Stauffacher M. Transdisciplinary case studies as a means of sustainability learning: historical framework and theory. *Int J Sustainab High Edu.* (2006) **7**:226–51. doi: 10.1108/14676370610677829
10. Tschakert P, Ricciardi V, Smithwick E, Machado M, Ferring D, Hausermann H, et al. Situated knowledge of pathogenic landscapes in Ghana: Understanding the emergence of Buruli ulcer through qualitative analysis. *Soc Sci Med.* (2016) **150**:160–171. doi: 10.1016/j.socscimed.2015.12.005
11. Eksvärd K. Facilitating systemic research and learning and the transition to agricultural sustainability. *J Agric Edu Extens.* (2010) **16**:265–280. doi: 10.1080/1389224X.2010.502759
12. Kapoor I. The devil's in the theory: A critical assessment of Robert Chambers' work on participatory development. Third *World Q.* (2001) **23**:101–17. doi: 10.1080/01436590220108199
13. Pretty J. Participatory learning for sustainable agriculture. *World Dev.* (1995) **23**:1247–63.
14. Fischer K, Chenais E, Torsson E, Wensman J. Where is the participation in participatory epidemiology? How engagement with social science could lead to improved understanding and control of Peste des Petits ruminants. *Br J Virol.* (2016) **3**:105–114. doi: 10.17582/journal.bjv/2016.3.4.105.114
15. McCracken J, Pretty J, Conway G. *An Introduction to Rapid Rural Appraisal for Agricultural Development.* London: IIED Sustainable Agriculture Programme (1988).
16. Jacobson K. *From Betterment to Bt maize: Agricultural Development and the Introduction of Genetically Modified Maize to South African Smallholders.* Ph.D. Doctoral theisis, Swedish University of Agricultural Sciences (2013).
17. Kaufmann B, Lelea M, Hulsebusch C. Diversity in livestock resources in pastoral systems in Africa. *Revue Sci Tech.* (2016) **35**:445–59. doi: 10.20506/rst.35.2.2535
18. Kasese District Local Government Statistical Abstract (2012). *Kasese District Local Government*. Available online at: http://www.ubos.org/onlinefiles/uploads/ubos/Kasese.pdf (Accessed Decemeber12, 2017).
19. UBOS (2014). *National population and housing census 2014. Provisonal results*. Uganda: Uganda bureau of statistics, Kampla, Uganda. Available online at: http://www.ubos.org/onlinefiles/uploads/ubos/NPHC/NPHC%202014%20PROVISIONAL%20RESULTS%20REPORT.pdf (Accessed March19, 2015).
20. Magona JW, Walubengo J, Olaho-Mukani W, Jonsson NN, Welburn SW, Eisler MC. Spatial variation of tick abundance and seroconversion rates of indigenous cattle to Anaplasma marginale, Babesia bigemina and Theileria parva infections in Uganda. *Exp Appl Acarol.* (2011) **55**:203–13. doi: 10.1007/s10493-011-9456-2
21. Radostits OM, Gay CC, Hinchcliff KW, Constable PD. *Veterinary Medicine E-Book: A Textbook of the Diseases of Cattle, Horses, Sheep, Pigs and Goats.* Philadelphia, PA: Elsevier Health Sciences (2006).
22. Urquhart G, Armour J, Duncan J, Dunn A, Jennings F. *Veterinary Parasitology*. Singapore: Longman (1996).
23. The Animal Diseases Act (1918). Available online at: http://www.ulii.org/ug/legislation/consolidated-act/38 (Accessed March 19, 2015).
24. Catley A, Okoth S, Osman J, Fison T, Njiru Z, Mwangi J, et al. Participatory diagnosis of a chronic wasting disease in cattle in southern Sudan. *Prev Vet Med.* (2001) **51**:161–181. doi: 10.1016/S0167-5877(01)00240-9
25. Ekou J. Dairy production and marketing in Uganda: Current status, constraints and way forward. *Afr J Agric Res.* (2014) **9**:881–8. doi: 10.5897/AJAR2013.8470
26. Byaruhanga C, Oosthuizen MC, Collins NE, Knobel D. Using participatory epidemiology to investigate management options and relative importance of tick-borne diseases amongst transhumant zebu cattle in Karamoja Region, Uganda. *Prev Vet Med.* (2015) **122**:287–97. doi: 10.1016/j.prevetmed.2015.10.011
27. Wolff C, Boqvist S, Ståhl K, Masembe C, Sternberg-Lewerin S. Biosecurity aspects of cattle production in Western Uganda, and associations with seroprevalence of brucellosis, salmonellosis and bovine viral diarrhoea. *BMC Vet Res.* (2017) **13**:382. doi: 10.1186/s12917-017-1306-y
28. Gachohi J, Skilton R, Hansen F, Ngumi P, Kitala P. Epidemiology of East Coast fever (Theileria parva infection) in Kenya: past, present and the future. *Parasit Vectors* (2012) **5**:194. doi: 10.1186/1756-3305-5-194
29. Mugerwa WK. *Rangeland Tenure and Resource Management: An Overview of Pastoralism in Uganda*. Kampala: Makerere Institute of Social Research (1992).
30. Rugadya MA. *Escalating Land Conflicts in Uganda. A Review of Evidence from Recent Studies and Surveys.* Washington, DC: The International Republican Institute and The Uganda Round Table Foundation (2009).
31. Coffin JL, Monje F, Asiimwe-Karimu G, Amuguni HJ, Odoch T. A One Health, participatory epidemiology assessment of anthrax (Bacillus anthracis) management in Western Uganda. *Soc Sci Med.* (2015) **129**:44–50. doi: 10.1016/j.socscimed.2014.07.037

32. Scoones I, Thompson J. *Beyond Farmer First: Rural People's Knowledge, Agricultural Research and Extension Practice*. London: Intermediate Technology Publications (1994).
33. Catley A, Alders RG, Wood JL. Participatory epidemiology: approaches, methods, experiences. *Vet J.* (2012) **191**:151–60. doi: 10.1016/j.tvjl.2011.03.010
34. Getchell J, Vatta A, Motswatswe P, Krecek R, Moerane R, Pell A, et al. Raising livestock in resource-poor communities of the North West Province of South Africa-a participatory rural appraisal study. *J South Afr Vet Assoc.* (2002) **73**:177–84. Available online at: http://journals.co.za/content/savet/73/4/EJC99503
35. Mochabo M, Kitala P, Gathura P, Ogara W, Eregae E, Kaitho T, et al. The socio-economic impact of important camel diseases as perceived by a pastoralist community in Kenya. *Onderstepoort J Vet Res.* (2006) **73**:269–274. Available online at: https://journals.co.za/content/opvet/73/4/EJC86272
36. Humblet MF, Vandeputte S, Albert A, Gosset C, Kirschvink N, Haubruge E, et al. Multidisciplinary and evidence-based method for prioritizing diseases of food-producing animals and zoonoses. *Emerg Infect Dis.* (2012) **18**. doi: 10.3201/eid1804.111151
37. Fèvre EM, Glanville WA, Thomas LF, Cook EA, Kariuki S, Wamae CN. An integrated study of human and animal infectious disease in the Lake Victoria crescent small-holder crop-livestock production system, Kenya. *BMC Infect Dis.* (2017) **17**:457. doi: 10.1186/s12879-017-2559-6

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A Systematic Evaluation of Measures Against Highly Pathogenic Avian Influenza (HPAI) in Indonesia

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Over the past years, many different control measures have been implemented to prevent HPAI infection. The national plan with numerous measures lead to problems in terms of prioritization and budget allocation. Our study objectives are to (i) establish an inventory of measures on HPAI control in Indonesia since the first actions were taken in 2004, (ii) evaluate preferences for different HPAI control measures applied in the West Java province at the district level during 2013–2017, and (iii) establish a basis for further qualitative and quantitative research to improve control for an endemic HPAI in Indonesia. This research was carried out according to the following five steps (i) development of an HPAI management framework for an endemic state, (ii) inventorization of measures directed at HPAI and description of the development of HPAI in Indonesia, (iii) development of a questionnaire for the experts involved, (iv) systematic evaluation of preferences for short- and long-term HPAI strategies and measures applied in the West Java Province based on expert opinion, and (v) data analysis. The study systematically evaluated in total 27 measures. The results of this study show that the animal disease management framework is helpful as a systematic structure to distinguish and evaluate strategies and measures. In our framework, we defined the following strategies: prevention, monitoring, control, mitigation, eradication, and human protection. The findings of our research show that the primary aims of the government were to safeguard humans from HPAI transmission by mitigating HPAI disease in livestock. The measures with the highest priority were preventive vaccination of poultry, biosecurity, and stamping-out infected flocks. This showed that the government predominantly chose a vaccination-based HPAI mitigation strategy. However, the chosen strategy has a low implementation feasibility. A collaboration between the responsible stakeholders farmers may increase the feasibility of the chosen strategy in the future. Furthermore, our findings provide a basis for research into the motivation of farmers to implement different measures as well as into the expected impact of different measures to develop an effective and efficient mitigation approach.

Keywords: HPAI H5N1, endemic, evaluation, measures, mitigation, strategy, vaccination

INTRODUCTION

The first major outbreak of Highly Pathogenic Avian Influenza (HPAI) H5N1 in Indonesia was in December 2003 (1). Since then, HPAI remained endemic in most regions in the country. HPAI is a zoonotic disease that severely infects both poultry and humans and has a high mortality rate [(2), p. 243]. During the outbreaks in 2003–2004, the Indonesian poultry industry suffered a loss of millions of US dollars through the death of millions of chickens and costs to control the spread of the disease [(3), p. 8]. Many small-scale poultry farmers stopped their activities and, as a consequence, lost their primary source of income, because the risk of infection was too high. Furthermore, there were 200 human-HPAI cases of which 168 were lethal (4).

The Indonesian government decided to regard HPAI H5N1 as one of the top priority zoonotic diseases due to the magnitude of its potential impact on the poultry industry and public health. A national strategic plan with measures to mitigate the HPAI epidemic was launched in 2006 [(5), p. 39–51). The formulation and implementation of the plan involved parties from ministries and international agencies, such as the Food and Agriculture Organization, World Organization of Animal Health (OIE), and the World Health Organization.

Over the past years, many different control measures have been implemented to prevent HPAI infection. The national plan with numerous measures lead to problems in terms of prioritization and budget allocation. In Indonesia, the autonomous district governments are mainly responsible for controlling HPAI, based on national guidelines. This decentralization has been argued to be an important challenge of controlling HPAI in Indonesia, because district governments may have their own judgement of measures to be implemented based on available financial and human resources as well as local support (6). Consequently, it is difficult to systematically evaluate the efficacy of each measure. In addition, academic literature mostly focuses on specific technical measures to control the disease either directly or indirectly, for instance, vaccination (7, 8), or participatory disease surveillance, and response (9). Considering the complexity of the issue, involving not only the HPAI virus but also animals and human actors (e.g., farmers, government), it is necessary to have a systematic evaluation of measures aimed to control HPAI. Currently, such an all-encompassing, systematic evaluation is lacking in Indonesia.

This paper aims to fill this gap by providing a systematic evaluation of HPAI control strategies in Indonesia. The objectives of this study are to (i) establish an inventory of measures on HPAI control in Indonesia since the first actions were taken in 2004, (ii) evaluate preferences for different HPAI control measures applied in the West Java province at the district level during 2013–2017, and (iii) establish a basis for further qualitative and quantitative research to improve HPAI control strategies in an endemic state in Indonesia.

MATERIALS AND METHODS

This research was carried out according to the following five steps (**Figure 1**): (i) development of an HPAI management framework for an endemic state, (ii) inventorization of measures directed at HPAI and description of the development of HPAI in Indonesia, (iii) development of a questionnaire for the experts involved, (iv) systematic evaluation of preferences for short- and long-term HPAI strategies and measures applied in the West Java Province, based on expert opinion, and (v) data analysis.

Step 1: Development of the HPAI Management Framework

Management of HPAI, particularly in an endemic state, is complex. This complexity makes it difficult to evaluate the efficacy of different measures, both for livestock and for the human health sector. A framework of animal disease management in the context of HPAI is essential to overcome this issue, especially in countries with endemic infections, such as Indonesia. In this study, we adapted the animal disease management framework of (10) to (i) provide a systematic inventory procedure for measures on HPAI in Indonesia, (ii) develop a questionnaire for evaluation, and (iii) combine the two into a systematic framework for measure evaluation.

Figure 2 depicts the HPAI management framework for an endemic HPAI that consists of six elements: *states*, *events* (i.e., the transition between states), *influencing factors* (i.e., factors that determine the probability and time interval with which a population remains in a given state or enters into a different state), *driving forces* (i.e., factors that both directly and indirectly influence the implementation of measures), *strategy* (i.e., a group of measures aimed at a particular event with the same purpose), and *measures* (i.e., an activity with one or more specific aims).

In comparison with the original framework, two additional *states* were added. The adapted framework consists of five mutually exclusive states: (i) AI-free, (ii) high-risk period (HRP), (iii) outbreaks (post-HRP), (iv) endemic (high), and (v) endemic (low). Since the nature of HPAI is zoonotic, we added an additional exhaustive state: (vi) human outbreak.

The AI-free state is defined as a district free of AI disease. The high-risk period (HRP) is defined as the period when the AI virus is present and can spread freely, but is not yet identified in a given district. Once HPAI has been identified—either through monitoring and surveillance activities or by a clinical outbreak in livestock or humans—the state of the outbreak (post-HRP) starts. The endemic state is defined as a state when there is a constant presence of AI cases or outbreaks within part of a district. In the context of this study, the endemic state is subdivided into two states: high or low HPAI prevalence. More specifically, as there is a lack of accurate data or reports about HPAI outbreaks, we defined a district with high HPAI prevalence as one where outbreaks occur in more than 50% of the sub-districts or when HPAI is identified in AI-free sub-districts. A low-prevalence endemic state is defined as a state where outbreaks of HPAI occur in <50% of the sub-districts, while AI-free sub-districts remain free of HPAI. The human outbreak state is defined as one or more human HPAI infections in a given district.

The framework includes five *events*: introduction, notification, eradication, mitigation, and transmission. Introduction means

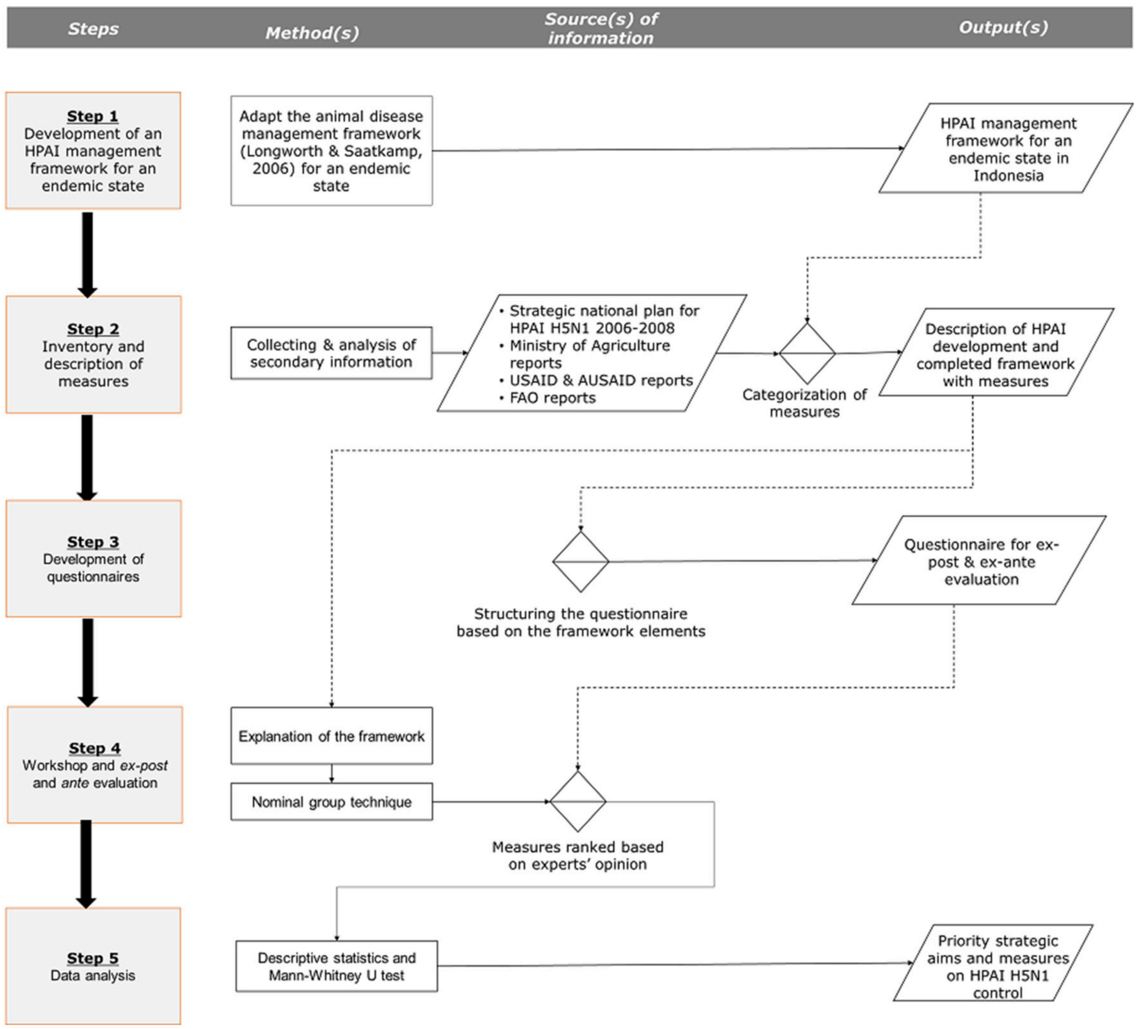

FIGURE 1 | Steps and approaches for the evaluation of measures directed at HPAI mitigation in Indonesia.

that the HPAI virus entered into an AI-free district. The presence of HPAI virus is detected and notified within the event of notification. After the disease has been notified, eradication will follow in which ideally control measures are applied to reduce the prevalence of HPAI to zero. When actions to eradicate are not sufficient, mitigation measures are put in place to reduce the prevalence of HPAI until control measures can eradicate the virus effectively. The event of transmission represents the passing of HPAI from animals to humans.

Influencing factors can be further divided into factors that are responsible for HPAI transmission either in livestock or in humans. A number of influencing factors of HPAI transmission in livestock have previously been identified, such as: rice cropping intensity, precipitation, farming/trade intensity, low elevation, road density, and backyard farm population [(11), p. 4–5; (12), p. 2–5; (13), p. 4–7; (14), p. 3–7). Likewise, several risk factors of HPAI transmission to humans have been identified, such as direct and indirect contact with a sick or dead bird, visiting a wet or live bird market, consuming sick poultry, and poor sanitation [(15), p. 1843–1845; (16), p. 1728–1733].

Driving forces can be either autonomous (global) or institutional. Autonomous driving forces include macroeconomic developments that have no direct link with the poultry industry, while institutional driving forces are local to national policies, which in this case are related to the Indonesian poultry industry and HPAI itself.

Coping with a disease event requires a *strategy*. Three additional strategies directed to HPAI were added to the original framework of (10) consists prevention, monitoring, and control in the EU context. While our adapted framework recognizes the endemic state and human-HPAI cases in Indonesia, therefore strategies of mitigation (i.e., minimize the number of outbreaks), eradication [(17), p. 1], and human protection [(5), p. 23–30] were added to the adapted framework. The strategy of prevention is a combination of measures that aim to reduce the likelihood of disease introduction into a domestic population.

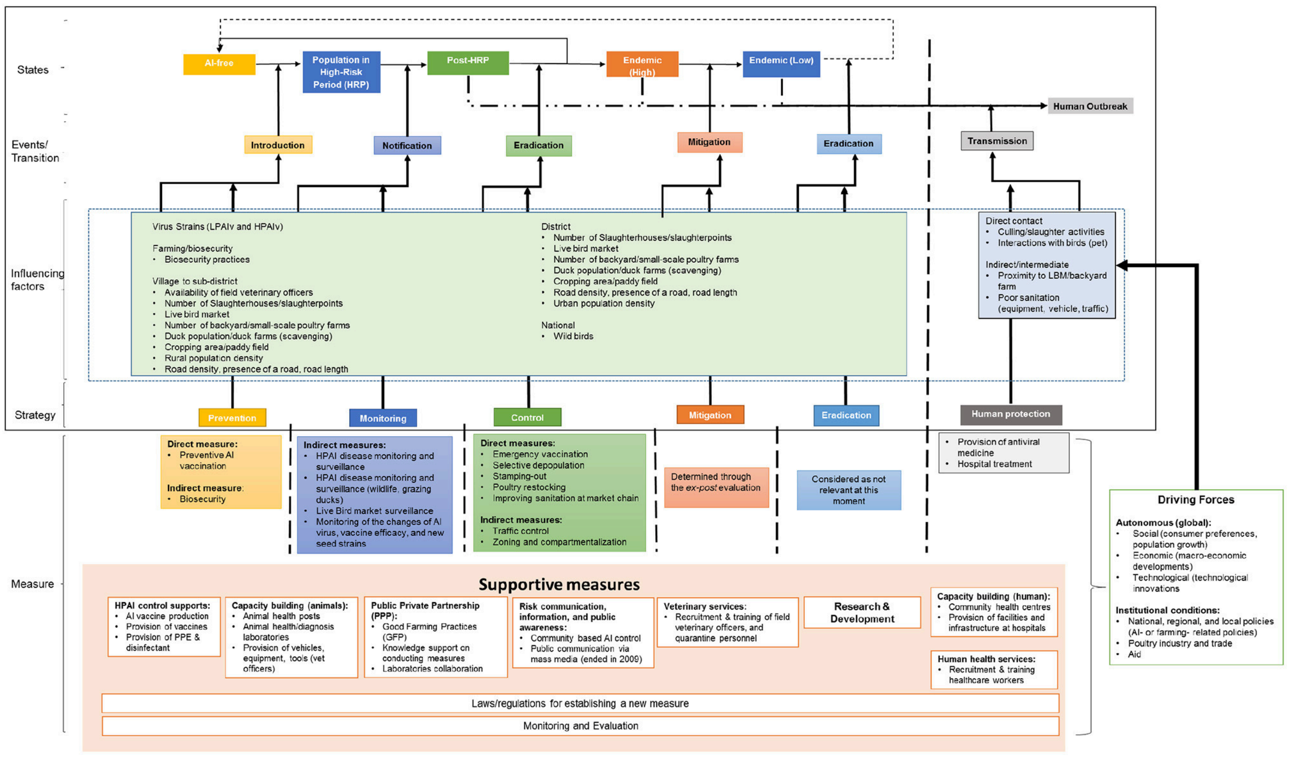

FIGURE 2 | HPAI management framework for the endemic state in Indonesia.

The strategy of monitoring is a combination of measures aimed to monitor and surveil a population to reduce the high-risk period. The strategy of control is a combination of measures aimed to eradicate the disease as quickly as possible. The strategy of mitigation involves a combination of measures aimed to reduce the prevalence of a disease to the extent that control measures can effectively eradicate the disease. The strategy of eradication involves a combination of measures aimed to completely eradicate a disease that already has a low prevalence. Both mitigation and eradication strategies consist of a combination of measures from prevention, monitoring, and control strategies. In our framework (**Figure 2**), mitigation and eradication strategies are intentionally left blank because district governments have the autonomy to implement different combinations of measures to suit the local context. The human protection strategy comprises a combination of measures aimed at reducing the risk of HPAI transmission from animals to humans and at treating HPAI patients. Within the context of this study, we focused on mitigation, eradication, and human protection strategies.

Measures are categorized, based on their aims, into three types: direct, indirect, and supportive measures. Direct measures have a direct impact on the virus and disease prevalence in livestock and humans. Indirect measures have an indirect impact at the prevalence in livestock and humans by reducing transmission and thus prevent further spread of the virus (i.e., to contain the virus). Supportive measures are all measures that are aimed at supporting the implementation of direct and indirect measures so that these measures can achieve their aim(s).

Our framework distinguishes different states, strategies, and measures. It allows a more structured evaluation of measures within a strategy as well as between two or more different strategies based on specific priorities or preferences.

Step 2: A Systematic Inventory of Measures

Using the developed framework, measures were systematically inventoried to complete the framework for designing the questionnaire and evaluating measures of HPAI control in Indonesia.

Most of the HPAI control programs in livestock and humans in Indonesia were project-based programs funded by other countries or external organizations (e.g., USA, EU, and Australia). The projects are based on national guidelines of HPAI control that were formulated by the government and external organizations (e.g., FAO and OIE). Thus, we collected information for the inventory of measures from the national strategic plan for HPAI H5N1 (5), the USAID report of its HPAI program (18) and Food and Agriculture Organization reports: Avian Influenza control program (19–21) and Emergency Center for Transboundary Animal Diseases (ECTAD) reports (22–25).

In total, we identified and briefly described 35 direct, indirect, or supportive measures for the prevention, monitoring, and control of HPAI since 2004 (see **Supplementary Material**). Next, these measures were grouped based on their focus, aim, the responsible actors, the targets of measure, the policy level, and year of implementation. Direct and indirect measures were listed under either the prevention, monitoring, or control strategy as defined in the evaluation framework, based on the purpose of each measure.

Step 3: Questionnaire Development

Based on our framework, we developed a questionnaire aimed at *ex-post* evaluation of the identified HPAI control measures during 2013–2017, and *ex-ante* evaluation of future priorities with regard to direct, indirect, and supportive measures. The questionnaire along with the framework can be used as an additional tool to improve current monitoring and evaluation practice in animal disease management.

The questionnaire was composed in English and translated into Bahasa Indonesia. The first author tested the questionnaire in Bahasa Indonesia with colleagues and then translated the questionnaire back to English for publication.

The questionnaire consists of six parts (**Table 1**): (i) state of the disease; (ii) priority HPAI impacts; (iii) priority strategic aims; (iv) preferences toward direct, indirect, and supportive measures; (v) the degree of success; and (vi) budget priorities. A sample questionnaire can be obtained from the **Supplementary Material**. The first five parts of the questionnaire were aimed at *ex-post* evaluation, while the sixth part was aimed at *ex-ante* evaluation. Each part contained a description informing participants of the specific aim.

The first part aimed to determine HPAI prevalence in the participant's district (high or low) during the years 2013–2017. As such, we aimed to increase the awareness of the participants in answering subsequent parts of the questionnaire, particularly in determining the priority of measures. In reality, HPAI prevalence in a given district was determined based on the reported cases in the respective administrative area and the definitions highlighted above.

The second and the third part of the questionnaire aimed to determine the rankings of importance for different HPAI impacts and strategic aims for HPAI control. In each part, participants were asked to rank HPAI impacts and strategic aims during 2013–2017.

In the fourth part, we probed for preferred direct, indirect, and supportive measures. Participants were asked to identify from three lists which measures were implemented during 2013–2017. Then, participants were asked to rank measures within each category of measures according to priority. In practice, the list of measures could be adapted to the local context during the questionnaire design process.

In the fifth part, we aimed to evaluate HPAI developments within a district based on four parameters: HPAI prevalence, new cases of HPAI, outbreaks in non-dominant poultry sectors (i.e., layer, ducks, native), and human cases of HPAI. Participants were asked to rate each parameter (1 = worsen, 2 = no change, or 3 = improvement) for each parameter. In practice, this part could be replaced with qualitative information instead.

The sixth and final part handled the consistency with which priority measures were selected. Participants were asked to decide which among all direct, indirect, and supportive measures should receive the highest and lowest budget. Information on budget use and planning could be included. This information is extremely valuable for planners and policy-makers.

TABLE 1 | Outlines of the questionnaire for the *ex-post* evaluation.

Framework	Purpose of the question	Measurement
1. State of disease	Determine the state of HPAI for each year	A: endemic (high) B: endemic (low)
2. Livestock/ Humans (focus)	Determine priority disease impacts	Ranking
3. Strategy	Determine priority strategic aims	Ranking
4. Measures (ex-post)	Determine priority direct, indirect, and supportive measures (in the past)	Ranking (only for implemented measures)
5. Performance	Evaluate the degree of success, identify key success and not essential measures	Rating (1–3)
6. Budget priority	Determine measures from direct, indirect, or supportive measures to have the highest and lowest budget allocation	Selection of measures

Step 4: Workshop and Evaluation

The primary purpose of the workshop was to collect expert opinions for the *ex-post* and *ex-ante* evaluation of measures on HPAI control in the West Java province at the district level. In this study, we evaluated HPAI strategies and measures in the context of West Java Province (**Figure 3**) because West Java has the largest poultry population in the country and accounts for 33% of the national broiler production (26). In addition, the province has been struggling to control HPAI since the first major outbreak of HPAI H5N1 in 2004. Thus, we argue that the results of this study might be useful for other regions in Indonesia that are also in an endemic state. In addition, the workshop was also aimed to present HPAI management framework as a tool to design animal disease control strategies and a framework to evaluate the programs for government officials (i.e., to improve decision-making). The workshop consisted of three activities:

i. introduction of the animal health management framework and its use for the evaluation and design of animal disease strategy, particularly in the case of HPAI;
ii. application of the questionnaire and developed framework to conduct an *ex-post* evaluation of (a) priority disease impacts, strategic aims, and measures, and (b) the degree of success of HPAI control at the district level during 2013–2017; and
iii. an *ex-ante* evaluation of preferred measures of HPAI mitigation or eradication at the district level.

FIGURE 3 | The geographical map of the Republic of Indonesia. **(A)** Provincial boundaries of Indonesia with the West Java Province is highlighted. **(B)** A zoomed map of West Java Province.

Participating Experts

All participants are active in HPAI management, either as policy-makers or as veterinarians. Moreover, all participants had at least 5 years of professional experience related to HPAI control.

The approach we used for the workshop is the Nominal Group Technique (NGT) (27), which preserves anonymity and ensures an equal contribution of all participants [(28), p. 656]. Instead of implementing the four phases of NGT, the workshop had two phases: individual voting and a round-robin session, because the other two phases, the idea (idea generation) and description of measures (clarification), had been established prior to the workshop [(28), p. 656].

In total, 18 experts (**Table 2**) were invited to participate in the workshop. We invited local authorities from the top-five districts in terms of poultry population in the West Java province and from the Subang veterinary centers to participate in the workshop. We invited two representatives for each district government (except Subang as a host): the head and senior staff of the animal health department. Representatives from Tasikmalaya were not able to participate, and the empty slots were opened up to additional experts from Subang district. A week before the workshop, an executive summary of the content of the workshop and a short description of the framework were sent to all participants.

Set-up of the Workshop

A 3 h workshop was conducted on 20 March 2018 in the Veterinary Center of Subang. The workshop was divided into two sessions: a presentation and an evaluation session (with sub-sessions of *ex-post* and *ex-ante* evaluation). The aim of the first session was to present an overview of the study, the objectives, and the framework.

The aim of the second session was to evaluate. For this purpose, participants were divided into two groups consisted of nine participants in each group which is enough and manageable for NGT [(28), p. 656]. Participants from the same institution were separated to avoid discussions between direct colleagues. Participants filled in the questionnaire manually.

The voting session was continued by a round-robin session. In this session, further steps for the planning and implementation of measures were discussed, adjusting currently planned steps. Each participant was encouraged to give his or her comments both verbally as well as in writing.

The second session was followed by a 15-min discussion for additional input and comments.

The workshops were organized in compliance to the codes of ethics for research involving human participants in both Indonesia and the Netherlands. These codes require that participants have to be well-informed about the aims of the research as well as about the anonymity of participants [stated in KNEPK (29); NETHICS (30)]. A short proposal with details of the objectives and the contents of the workshop was sent to all participants before the workshops were held. Before the second session of the workshop, participants were informed about the purposes, and contents of the evaluation session and were asked for their consent. All data were analyzed and reported anonymously. The workshop was conducted by the first and second author

TABLE 2 | List of experts present at the workshop.

Regencies/ Province	Department	Type	Invited	Participation
1. Subang	Animal health	Government	5	7 (two replacement for participants from Tasikmalaya)
2. Tasikmalaya	Animal health	Government	2	–
3. Ciamis	Animal health	Government	2	2
4. Sukabumi	Animal health	Government	2	2
5. Bogor	Animal health	Government	2	2
6. West Java Province	Animal health	Government	2	2
7. Subang	State Polytechnic	Academic	1	1
8. Subang	Veterinary centers	Government	2	2

together with two facilitators who were trained before the workshop.

Step 5: Data Analysis

Non-parametric statistics were used to determine the difference between the rankings of measures. We used the Mann-Whitney U test to test the difference of the median scores (i.e., priority or preference) for each pair of HPAI impacts, strategic aims, direct measures, indirect measures, and supportive measures. Measures were ranked based on the difference on the *z*-score. Statistical analyses were performed using SPSS version 23.0 [IBM SPSS for Windows, Armonk, NY: IBM Corp (31)].

RESULTS

In the workshop, participants were asked to rank HPAI impacts and strategic aims as well as direct, indirect, and supportive measures separately.

Table 3 summarizes the experts' responses and rankings (1 = highest, 7 = lowest) of HPAI impacts during 2013–2017. It is clear that minimizing HPAI impact on public health and production (i.e., increased poultry mortality) were the main concerns of the local authorities. Regarding specific impacts of HPAI, the top priority impacts are human casualties due to HPAI, increased mortality of poultry, and human-HPAI cases. Reducing the morbidity rate for poultry and biosecurity improvement during an outbreak received lower priority. The lowest priority was assigned to loss of market access for farmers and birds due to culling.

Table 4 summarizes the experts' responses and rankings (1 = highest, 3 = lowest) for the aims of HPAI control during 2013–2017. The findings suggest that controlling HPAI and protecting the public from HPAI were the top priorities for

TABLE 3 | Experts' responses and rankings for HPAI impacts during 2013–2017 (N = 17).

Categories of impacts	Impacts of HPAI *	Mean (SE)	Mdn	Rank
On-farm (livestock)	Increase in morbidity rate of poultry[b,c,d]	3.82 (0.37)	4	4
	Increase in mortality rate of poultry[a,b]	2.94 (0.35)	3	2
	Improvement of farm biosecurity[d,e]	4.47 (0.36)	4	5
	Loss of birds due to culling[f]	5.94 (0.23)	6	7
Off-farm (livestock)	Loss of market access for the farmers[e,f]	5.41 (0.36)	5	6
Public Health	Human case of HPAI[b,c]	3.06 (0.40)	2	3
	Death case of humans[a]	2.29 (0.57)	1	1

means sharing the same superscript are not significantly different from each other (Mann Whitney U, $p < 0.05$).

TABLE 4 | Experts' responses and rankings for priority strategic aims (N = 17).

Aims*	Mean (SE)	Mdn	Rank
Mitigation of HPAI[a]	1.65 (0.15)	2	1
Human protection[a]	1.65 (0.21)	1	=1
Eradication of HPAI	2.59 (0.12)	3	2

means sharing the same superscript are not significantly different from each other (Mann Whitney U, $p < 0.05$).

the local governments. On the other hand, eradicating HPAI was considered a long-term aim, secondary to the top priority aims. In other words, the local governments prioritized public protection from the risk of HPAI transmission by controlling the disease within the poultry chains.

Table 5 summarizes the experts' responses and preference rankings (1 = highest, 5 = lowest) for direct HPAI prevention and control measures. Preventive AI vaccination (*Mean* = 1.35) was ranked significantly higher than the other direct measures, thus, it was considered the top priority direct measure. Direct measures with lower priority are ring vaccination and cleaning and disinfection. Stamping-out and selective depopulation were ranked at lowest priority.

Table 5 also summarizes the experts' responses and preference rankings (1 = highest, 8 = lowest) for indirect prevention, monitoring, and control measures. Biosecurity (*Mean* = 1.24) and monitoring the types of AI virus (*Mean* = 7) were ranked significantly higher and lower, respectively, than other indirect measures, indicating that biosecurity is the top priority among different indirect measures, while monitoring of HPAI virus type is the lowest priority. Indirect measures with lower priority were surveillance at farms and villages, zoning and compartmentalization, and traffic control.

Preference rankings for supportive measures in controlling HPAI are summarized in **Table 5** as well, with 1 indicating the highest ranking and 14 the lowest. Provision of AI vaccines for sector 3 and 4 farms (*Mean* = 2.63) was ranked significantly

TABLE 5 | Experts' responses and rankings for direct, indirect, and supportive measures.

Measures*	*N*	Mean (SE)	Mdn	Rank
DIRECT MEASURES				
Preventive AI vaccination	17	1.35 (0.21)	1	1
Emergency (ring) AI vaccination[a]	15	2.47 (0.27)	2	2
Poultry restocking (Cleaning & Disinfection)[a,b]	16	2.75 (0.21)	3	3
Stamping-out[a,b,c]	6	3.50 (0.50)	4	4
Selective depopulation[c]	12	3.58 (0.29)	4	=4
INDIRECT MEASURES				
Biosecurity	17	1.24 (0.18)	1	1
Surveillance (villages and farms)[a]	16	2.88 (0.29)	2	2
Zoning and compartmentalization[a,b]	16	3.63 (0.40)	4	3
Traffic control[a,b,c]	8	3.63 (0.71)	4	=3
Sanitation for transporting vehicles & markets[b,c,d,e]	12	4.50 (0.42)	5	4
Surveillance (wild birds & grazing ducks)[b,c,d,e]	10	4.60 (0.37)	5	=4
Live bird market (LBM) surveillance[b,c,d]	16	4.75 (0.48)	6	5
Monitoring types of AI virus	8	7.00 (0.42)	8	6
SUPPORTIVE MEASURES				
Provision of AI vaccines for sector 3 and 4 farms	16	2.63 (0.64)	1	1
Training farmers about prevention, monitoring, and control of HPAI[a]	15	3.80 (0.55)	4	2
Provision of cold storages for AI vaccines[a,b]	13	4.23 (0.75)	4	3
Community-based AI control[a,b,c]	15	4.33 (0.70)	4	=3
Good Farming Practices (GFP) training for famers' groups[b,c,d]	15	5.47 (0.55)	5	4
Building and improving animal health posts (Puskeswan)[c,d,e]	16	6.13 (0.64)	6	5
Public communication (mass media, flyers)[d,e,f]	15	6.53 (0.77)	7	6
Monitoring and evaluation[d,e,f,g]	16	7.13 (0.95)	7	7
Supporting facilities for field officers[d,e,f,g,h]	10	7.30 (0.72)	8	=7
Building and improving animal health laboratories[e,f,g,h,i]	9	7.67 (1.04)	8	=7
Regulations[d,e,f,g,h,i,j,k]	9	8.11 (1.18)	9	8
Laboratories collaborations[f,g,h,i,j]	14	8.29 (0.63)	8	9
Research[k]	8	10.88 (0.83)	11	10
Provision of Personal Protective Equipment (PPE)**	1	5.00 (0.00)	5	11

[*]means sharing the same superscript in their respective category (i.e., direct, indirect, and supportive) are not significantly different from each other (Mann Whitney U, $p < 0.05$).
[**]excluded from statistical analysis.

higher than the other supportive measures, suggesting that it is the top priority supportive measure. Lower priority supportive measures (ranking 2–4) include provision of supporting facilities for vaccination programs and training farmers with regard to HPAI control.

TABLE 6 | Summary of responses for the degree of success of HPAI control (*N* = 17).

The degree of success of HPAI control strategies	Mean (SE)	Rank
HPAI prevalence on broiler sector	2.76 (0.16)	2
New cases of HPAI in AI-free sub-districts	2.59 (0.17)	3
Outbreaks on duck, layer and native chicken farms	2.76 (0.16)	2
Human-HPAI case	3.00 (0.00)	1

Table 6 summarizes the ratings (1 = worsen, 2 = no change/same condition, 3 = improvement) on the condition of each parameter of HPAI state development during 2015–2017. In addition, the perceived degree of success of HPAI control measures was evaluated using four parameters. The results show an overall improvement on all parameters. Human-HPAI cases (*Mean* = 3) were perceived to be reduced. This result is in line with the actual number of reported human-HPAI cases during 2015–2017 (4). In addition, experts also perceived that the number of HPAI outbreaks had decreased on broiler farms (*Mean* = 2.76); on duck, layer, and native chickens farms (*Mean* = 2.76); and (3) in AI-free regions (*Mean* = 2.59). However, the scores also indicate room for improvement as there are districts that still have outbreaks. The scoring may be affected by a lack of information about HPAI outbreaks due to underreporting by farmers and limited surveillance by the government.

In addition to the *ex-post* evaluation, the *ex-ante* evaluation helped to determine the preferred budget allocations toward different measures within two different budget constraint scenarios. **Table 7** summarizes the number of votes on the highest and lowest budget allocation among direct, indirect, and supportive measures. This evaluation aims to look at whether preferences for top priority measures are still consistent when phrased in terms of financial resource allocation.

In current budget constraints, measures with the highest budget allocation were preventive AI vaccination (7), biosecurity (3), and stamping-out (2), while the lowest budget allocation went to zoning and compartmentalization (5), poultry restocking (3), training of farmers for prevention and control of HPAI (2), and public communication (2).

In a scenario with more stringent budget constraints, measures with the highest budget allocation were preventive AI vaccination (7), public communication (3), and stamping-out (2). The lowest allocation of budget was for zoning and compartmentalization (5), and selective depopulation (2).

The results show that preventive AI vaccination is consistently rated as a top priority measure. Combining the results of both *ex-post* (**Table 5**) and *ex-ante* (**Table 7**) evaluation, we created a list of preferential measures of the government including budget allocation priorities (**Table 8**). This table lists the priorities from all categories of measures: (1) preventive AI vaccination, (2) biosecurity, and (3) stamping-out. The budget allocation consistently underscores the top priority measures from each category of measures, even though provision of AI vaccines received only one vote. This is because the government usually provides AI vaccines during the wet season or if an outbreak

TABLE 7 | List of measures with the number of voting for highest and lowest budget allocation.

Category	Measures	Budget scenario 1*: same		Budget scenario 2**: lesser	
		Highest[a] (*N* = 16)	Lowest[a] (*N* = 15)	Highest (*N* = 14)	Lowest (*N* = 12)
Direct	Preventive AI vaccination	7	–	7	–
Direct	Stamping-out	2	–	2	–
Indirect	Biosecurity	3	–	1	–
Supportive	Public communication	3	2	3	1
Supportive	Provision of AI vaccines	–	–	1	–
Supportive	Building and improving animal health posts	1	–	–	–
Supportive	Community-based AI control	–	1	–	–
Direct	Selective depopulation	–	–	–	2
Supportive	Regulations	–	1	–	1
Supportive	Monitoring and evaluation	–	1	–	1
Supportive	Training of farmers (prevention and control of HPAI)	–	2	–	1
Direct	Poultry restocking (cleaning & disinfection)	–	3	–	1
Indirect	Zoning and Compartmentalization	–	5	–	5

*budget scenario 1: similar amount/percentage of budget for HPAI in the future.
**budget scenario 2: lower budget for HPAI in the future.
[a]highest/lowest: number of voting for which measures are preferred to have the highest/lowest budget allocation.

TABLE 8 | List of priority direct, indirect, and supportive measures for mitigation strategy.

Measures	Priority	Budget allocation priority
DIRECT MEASURES		
Preventive AI vaccination	1	Very high
Emergency (ring) vaccination	2	N.A.
Poultry restocking	3	Very low
Stamping-out	4	High
INDIRECT MEASURES		
Biosecurity	1	High
Surveillance (village and farms)	2	None
Traffic Control	3	None
Zoning and compartmentalization	3	Very Low
SUPPORTIVE MEASURES		
Provision of AI vaccines	1	Mid
Training of farmers for HPAI prevention, monitoring, and control of HPAI	2	Very low
Cold-chain for AI vaccine storages	3	N.A.
Community-based AI control program	3	Low

occurs. Although stamping-out is not a priority measure, the compensation can take up a substantial portion of the budget.

DISCUSSION

This study carried out a systematic evaluation of measures directed at HPAI mitigation in the West Java Province of Indonesia. The study was carried out in different steps: development of an HPAI management framework for an endemic state, inventorization of measures, design of a questionnaire, and *ex-post* and *ex-ante* evaluations of measures through a half-day workshop with experts.

The results of this study show that the animal disease management framework is helpful as a systematic structure to distinguish and evaluate strategies and measures. The use of our framework can also be extended to the evaluation of strategies and measures for other zoonotic infectious diseases within a one health approach. The NGT approach proved to be fruitful for the workshop conducted as part of this study. Results from the first round of voting round were not shown to participants and a second round of ranking/voting could not be conducted because of time constraints. Based on the objective of this study, most participants in the workshop were government officials because the officials have knowledge and experience about the implementation of measures on the fields and are the planners and decision-makers of HPAI strategies within their respective districts. Thus, we did not include other expertise, for instance, representatives of farmer groups who are the subjects of the strategies. In addition, this study did not review the governance of control, the role of the national government, of local governments, and of international organizations that even may fund a part of the control. We argue that a further study which focuses on this particular topic would be interesting.

HPAI Mitigation Priorities for Local Governments

By carrying out the evaluation, this study identified priority aims, impacts, and preferred measures (i.e., direct, indirect, and supportive) for HPAI control in the West Java Province. Two primary aims of the local government directed to HPAI were identified: protecting humans from HPAI and reducing the prevalence of HPAI on poultry farms. Eradication, which is the legally mandatory aim in most Western countries, was not a main aim for the Indonesian local governments. This implies an HPAI strategy that is aligned with the aim of HPAI mitigation. The priority aims are also reflected in the ranking of disease impacts, where effects on public health and farms (e.g., mortality and morbidity rate) stand out.

The preferred *direct measures* were consistent with the impact and aims. The high preference of vaccination is consistent with the priority of prevention of HPAI infection to birds (i.e., mitigation) and transmission to humans (i.e., protection).

Moreover, the low preference given to measures of total and selective culling were consistent with the low priority of an HPAI impact on loss of birds due to culling.

For the *indirect measures*, the high preference of biosecurity was consistent with vaccination. In order to increase the success rate of vaccination, improvement and uptake of biosecurity measures are essential [(32), p. 71]. Lower preference was given to surveillance on farms and villages. Surveillance measures are critical to provide all stakeholders with information about the prevalence of AI and other avian diseases as well as to ensure the proper implementation of vaccination. Such information can be used to stimulate farmers to improve animal health management. Although the monitoring of AI virus types was considered as the least preferred among indirect measures, it is important to note that information with regard to the variation in types or clades of AI virus across different districts may be beneficial for the implementation of suitable prophylactic vaccination. Especially in an endemic state, systematic implementation of vaccination against the same type of HPAI virus circulating in poultry is important [(33), p. 10]. Such information will also aid the development of a more effective AI vaccine, and therefore, a more successful vaccination program.

The findings on preferred *supportive measures* are consistent with the preference for vaccination. Provision of AI vaccines and the availability of cold storage may enable farmer access to HPAI vaccines. Furthermore, supportive measures related to farmer training on HPAI control are also essential to increase the low uptake of proper vaccination and biosecurity measures.

Overall, HPAI control measures with the highest preference, such as preventive vaccination, biosecurity, and stamping-out, coincided with the priority aims of the local government. Measures receiving lower preference were emergency vaccination, surveillance at the village and farm level, and provision of vaccines.

Based on these results, the preferred path for a HPAI control strategy which is in line with the strategy preferences would be vaccination-based mitigation to safeguard human and poultry livestock. This is consistent with the findings from a study on risk factors for poultry outbreak in the West Java Province by Yupiana et al. (12). The authors suggest that the most effective way to prevent the spread of HPAI (i.e., to humans and livestock) is by implementing preventive and control measures on poultry farms. A main subsequent issue, therefore, is whether this preferred strategy is feasible to be practically implemented in West Java. However, one might question how feasible vaccination-based HPAI mitigation is in Indonesia, particularly in West Java.

Feasibility of Vaccination-Based HPAI Mitigation in West Java Province

Vaccination strategies can only be effective if governments are consistent when implementing measures, even if there is a serious budget constraint. The implementation of vaccination also depends on farmer behavior, as farmers need to implement vaccination measures on their farms. They might do so out of self-interest (i.e., higher benefits than costs) or for the benefit of the public and their relatives (i.e., by preventing HPAI transmission to humans).

For a vaccination-based mitigation strategy to be successful, i.e., to protect humans, the coverage and the efficacy of vaccination as well as the uptake of biosecurity measures should be sufficient [(32), p. 71; (33), p. 8; (34), p. 70; (35), p. 10]. In the Indonesian context, a large improvement on both levels and on a long-term basis is needed.

The *coverage* of HPAI vaccination remains low in Indonesia due to the low uptake of vaccination by farmers. Vaccination is less common in broiler farms due to the short production cycle, particularly in sector 3 and 4 farms, which are the main suppliers in the traditional market channel. Vaccination is more common in layer farms because these farms have appropriate equipment and trained staff [(36), p. 12]. In addition, a single AI vaccination is not sufficient to give full protection for broiler chickens before they are slaughtered [(35), p. 10]. Immunity can only be achieved after two vaccinations, making the process either more expensive or less effective. Therefore, some farmers do not favor vaccination. In contrast, poultry farmers working with a longer production cycle, i.e., native and layer chicken farmers, may have a more positive attitude toward vaccination, as the benefit of vaccination can outweigh the implementation cost. The total coverage of HPAI vaccination is far from sufficient.

Regarding the *efficacy* of AI vaccines, several studies have shown that AI vaccines are not effective to prevent the spread of HPAI H5N1 in broiler and layer chickens [(35), p. 10; (37), p. 639; (38), p. 9–12). The efficacy of vaccines also partially depends on how well they target certain strains of AI virus, for instance. Thus, production and provision of AI vaccines that are suitable for various strains of HPAI virus is essential to increase the efficacy of any vaccination program. Governmental monitoring and surveillance activities can help to identify which specific strains of AI virus circulate in a particular region and, consequently, a suitable vaccine can be identified for local use.

Increasing the efficacy of vaccination also requires a *proper implementation* of vaccination. In the context of West Java Province, the broiler production sector includes a four different farm types, that can be categorized, based on their level of biosecurity (FAO). Large industrial integrated broiler farms with high biosecurity (sector 1); medium- to large-scale commercial broiler farms with moderate to high biosecurity (sector 2); small- to medium-scale commercial broiler farms with low biosecurity (sector 3); and backyard broiler farms with low biosecurity and a small number of birds per farm (sector 4) [(36), p. 9]. Although the sector 1–4 categorization started to be used for biosecurity reasons, it is often also used for a position in the value chain. Sector 1 farms always market their chickens in the modern channel; sector 2 farms mostly market their chickens in the modern channel but sometimes to the traditional channel through private collecting farms; and sector 3 and 4 farms always market their chickens in the traditional channel [(39), p. 6]. Farms in sectors 1 and 2 have more capabilities and resources to conduct a proper vaccination as well as to control the disease in case of an outbreak. As a consequence, the implementation of vaccination is often lacking or poorly implemented in sector 3 and 4 farms. This condition is exacerbated by the fact that there is a market for sick poultry, reducing the economic consequences of HPAI outbreaks for broiler farms. This may in turn reduce the motivation of farmers to vaccinate and improve biosecurity, hampering HPAI control in Western Java [(39), p. 10]. Thus, vaccination to control HPAI need more emphasis for sector 3 and 4 farms rather than sector 1 and 2 farms.

In the context of the West Java Province, vaccination-based HPAI mitigation requires a more active collaboration between government, integrated companies, and farmers in different districts. Such collaborations can open opportunities for new HPAI mitigation schemes. Certain schemes may stimulate stakeholders to act in the public interest, i.e., to control HPAI. As a result, achieving the aims to safeguard both humans and birds from HPAI would become more feasible. Although desirable, vaccination-based mitigation strategies were found to be inefficient in Indonesia where there are many sector 3 and 4 farms spread in rural regions. Therefore, an alternative strategy has to be considered.

Alternatives to Control HPAI

Vaccination-based HPAI mitigation may result in endemicity and antigenic drift of the viral strain [(33), p. 1]. A non-vaccination mitigation strategy could be considered as a second alternative, targeted to the actors in the value chain.

One might consider prioritizing biosecurity measures to mitigate the spread of HPAI [(40), p. 7]. The improvement of biosecurity measures on sector 3 and 4 farms can focus on basic measures such as sanitation of the farm and the personnel, and strict access control to the farm. Biosecurity measures are poorly implemented in sector 3 and 4 farms in Indonesia [(36), p. 9; (39), p. 8]. However, basic biosecurity measures alone do not necessarily reduce the mortality rates in poultry within a backyard setting [(41), p. 650–654]. Thus, vaccination and monitoring and surveillance measures for farms and villages need to be retained in the strategy but will receive lower priority. Monitoring the implementation of biosecurity measures is essential for the correct application of measures as well as to shape new habits with farmers.

Biosecurity measures need to be applied not only by farmers, but also other stakeholders such as buyers, for instance by disinfecting the cars and the crates that are used to transport poultry. Modifying transportation cars into semi-closed vehicles with a fan may also help to reduce the spread of HPAI during transport of live birds.

CONCLUSIONS

From this research, we conclude that the aim of the local governments in West Java is to protect humans and livestock from HPAI. Governmental experts prefer vaccination-based mitigation to safeguard humans and poultry. Eradication is considered a long-term goal.

Based on the aim, selected strategies are identified: mitigation and human protection. Coinciding with the priority aims, the top preferred measures identified by the experts are: vaccination, biosecurity, stamping-out, and provision of AI vaccines. However, the feasibility of vaccination-based HPAI mitigation is low, particularly in sector 3 and 4 broiler farms (e.g., low efficacy of vaccines and limited uptake of measures). A collaboration between the government, integrated companies, and farmers may help to increase the feasibility of either a vaccination- or biosecurity-based mitigation strategy.

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.

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SUPPLEMENTARY MATERIAL

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REFERENCES

1. World Organisation for Animal Health (OIE). *Highly Pathogenic Avian Influenza in Indonesia (2004)*. Available online at: http://www.oie.int/en/animal-health-in-the-world/update-on-avian-influenza/2004/ (Accessed October 23, 2018)
2. Peiris JS, de Jong MD, Guan Y. Avian influenza virus (H5N1) a threat to human health. *Clin Microbiol Rev.* (2007) 20:243–67. doi: 10.1128/CMR.00037-06
3. Basuno E, Yusdja Y, Ilham N. Socio-economic impacts of avian influenza outbreaks on small-scale producers in indonesia. *Transbound Emerg Dis.* (2010) 57:7–10. doi: 10.1111/j.1865-1682.2010.01121.x
4. World Health Organization (WHO). *Cumulative Number of Confirmed Human Cases of Avian Influenza A(H5N1) Reported to WHO 2003-2018* (2018). Available online at: http://www.who.int/influenza/human_animal_interface/2018_03_02_tableH5N1.pdf?ua=1 (Accessed May 31, 2018).
5. Ministry of National Development Planning (MoNDP). *National Strategic Plan For Avian Influenza Control and Pandemic Influenza Preparedness 2006–2008*. (2006). p. 1–75.
6. Forster P. *The Political Economy of Avian Influenza in Indonesia.* STEPS Working Paper 17. Brighton: STEPS Centre. (2009).

7. Bett B, McLaws M, Jost C, Schoonman L, Unger F, Poole J, et al. The effectiveness of preventative mass vaccination regimes against the incidence of highly pathogenic avian influenza on Java Island, Indonesia. *Transbound Emerg Dis.* (2015) 62:163–73. doi: 10.1111/tbed.12101
8. Walker PG, Jost C, Ghani AC, Cauchemez S, Bett B, Azhar M, et al. Estimating the transmissibility of H5N1 and the effect of vaccination in Indonesia. *Transbound Emerg Dis.* (2015) 62:200–8. doi: 10.1111/tbed.12108
9. Azhar M, Lubis AS, Siregar ES, Alders RG, Brum E, McGrane J, et al. Participatory disease surveillance and response in Indonesia: strengthening veterinary services and empowering communities to prevent and control highly pathogenic avian influenza. *Avian Dis.* (2010) 54:749–53. doi: 10.1637/8713-031809-Reg.1
10. Longworth NJ, Saatkamp HW. A conceptual framework for analyzing strategies for prevention, monitoring and control of Avian Influenza. In *12th European Poultry Conference.* Verona, Italy (2006). p. 62:101.
11. Fang LQ, de Vlas SJ, Liang S, Looman CW, Gong P, Xu B, et al. Environmental factors contributing to the spread of H5N1 avian influenza in mainland China. *PLoS ONE* (2008) 3:e2268. doi: 10.1371/journal.pone.0002268
12. Yupiana Y, de Vlas SJ, Adnan NM, Richardus JH. Risk factors of poultry outbreaks and human cases of H5N1 avian influenza virus infection in West Java Province, Indonesia. *Int J Infect Dis.* (2010) 14:e800–5. doi: 10.1016/j.ijid.2010.03.014
13. Martin V, Pfeiffer DU, Zhou X, Xiao X, Prosser DJ, Guo F, et al. Spatial distribution and risk factors of highly pathogenic avian influenza (HPAI) H5N1 in China. *PLoS Pathogens* (2011) 7:e1001308. doi: 10.1371/journal.ppat.1001308
14. Si Y, de Boer WF, Gong P. Different environmental drivers of highly pathogenic avian influenza H5N1 outbreaks in poultry and wild birds. *PLoS ONE* (2013) 8:e53362. doi: 10.1371/journal.pone.0053362
15. Dinh PN, Long HT, Tien NT, Hien NT, Mai TQ, Phong H, et al. Risk factors for human infection with avian influenza A H5N1, Vietnam, 2004. *Emerging Infect Dis.* (2006) 12:1841–7. doi: 10.3201/eid1212.060829
16. Zhou L, Liao Q, Dong L, Huai Y, Bai T, Xiang N, et al. Risk factors for human illness with avian influenza A (H5N1) virus infection in China. *J Infect Dis.* (2009) 199:1726–34. doi: 10.1086/599206
17. World Organisation for Animal Health (OIE). *Guidelines for Animal Disease Control. (2014).* Available online at: https://www.oie.int/fileadmin/Home/eng/Our_scientific_expertise/docs/pdf/A_Guidelines_for_Animal_Disease_Control_final.pdf (Accessed January 2, 2019).
18. United States Agency for International Development. *USAID USAID/Indonesia Avian and Pandemic Influenza (API) Program Evaluation: 2009–2014.* (2014).
19. Food and Agriculture Organization of the United Nations (FAO). *Avian Influenza Control Programme Annual Report 2008* (2008).
20. Food and Agriculture Organization of the United Nations (FAO). *Avian Influenza Control Programme Annual Report 2009* (2009).
21. Food and Agriculture Organization of the United Nations (FAO). *Avian Influenza Control Programme Annual Report 2010* (2010).
22. Food and Agriculture Organization of the United Nations (FAO). *Emerging Centre for Transboundary Animal Diseases (ECTAD) Annual Report 2011* (2011).
23. Food and Agriculture Organization of the United Nations (FAO). *Emerging Centre for Transboundary Animal Diseases (ECTAD) Annual Report 2011* (2012).
24. Food and Agriculture Organization of the United Nations (FAO). *Emerging Centre for Transboundary Animal Diseases (ECTAD) Annual Report 2011* (2013).
25. Food and Agriculture Organization of the United Nations (FAO). E*merging Centre for Transboundary Animal Diseases (ECTAD) Annual Report 2011* (2014).
26. Central Bureau of Statistics. (2018). (BPS) *Produksi Daging Ayam ras Pedaging Menurut Provinsi, 2009-2017.*Available online at: https://www.bps.go.id/linkTableDinamis/view/id/1064/ (Accessed December 13, 2018).
27. Delbecq AL, Van de Ven AH, Gustafson DH. *Group Techniques for Program Planning: A Guide to Nominal Group and Delphi Processes*. Glenview, IL: Scott, Foresman (1975).
28. McMillan SS, King M, Tully MP. How to use the nominal group and Delphi techniques. *Int J Clin Pharm.* (2016) 38:655–62. doi: 10.1007/s11096-016-0257-x
29. KNEPK. *Edoman Nasional Etik Penelitian Kesehatan* (2011). Available online at: http://www.ke.litbang.kemkes.go.id/kom14/wp-content/uploads/2017/12/Pedoman-Nasional-Etik-Penelitian-Kesehatan-2011-Unedited-Version.pdf (Accessed December 20, 2018).
30. NETHICS. *Code of Ethics for Research in the Social and Behavioural Sciences Involving Human Participants* (2018). Available online at: http://www.nethics.nl/Gedragscode-Ethical-Code/ (Accessed December 20, 2018).
31. IBM Corp. Released. *IBM SPSS Statistics for Windows, Version 23.0*. Armonk, NY: IBM Corp. (2015).
32. Marangon S, Cecchinato M, Capua I. Use of vaccination in avian influenza control and eradication. *Zoo Public Health* (2008) 55:65–72. doi: 10.1111/j.1863-2378.2007.01086.x
33. Peyre M, Fusheng G, Desvaux S, Roger F. Avian influenza vaccines: a practical review in relation to their application in the field with a focus on the Asian experience. *Epidemiol Infect.* (2009) 137:1–21. doi: 10.1017/S0950268808001039
34. Capua I, Alexander DJ. Avian influenza vaccines and vaccination in birds. *Vaccine* (2008) 26:D70–3. doi: 10.1016/j.vaccine.2008.07.044
35. Poetri O, Bouma A, Claassen I, Koch G, Soejoedono R, Stegeman A, et al. A single vaccination of commercial broilers does not reduce transmission of H5N1 highly pathogenic avian influenza. *Vet Res.* (2011) 42:74. doi: 10.1186/1297-9716-42-74
36. Wibawa H, Karo-Karo D, Pribadi ES, Bouma A, Bodewes R, Vernooij H, et al. Exploring contacts facilitating transmission of influenza A (H5N1) virus between poultry farms in West Java, Indonesia: a major role for backyard farms? *Prev Vet Med.* (2018) 156:8–15. doi: 10.1016/j.prevetmed.2018.04.008
37. Poetri ON, Van Boven M, Claassen I, Koch G, Wibawan IW, Stegeman A, et al. Silent spread of highly pathogenic avian influenza H5N1 virus amongst vaccinated commercial layers. *Res Vet Sci.* (2014) 97:637–41. doi: 10.1016/j.rvsc.2014.09.013
38. Tarigan S, Wibowo MH, Indriani R, Sumarningsih S, Artanto S, Idris S, et al. Field effectiveness of highly pathogenic avian influenza H5N1 vaccination in commercial layers in Indonesia. *PLoS ONE* (2018) 13:e0190947. doi: 10.1371/journal.pone.0190947
39. Indrawan D, Rich KM, van Horne P, Daryanto A, Hogeveen H. Linking supply chain governance and biosecurity in the context of HPAI control in Western Java: a value chain perspective. *Fron Vet Sci.* (2018) 5:94. doi: 10.3389/fvets.2018.00094
40. Conan A, Goutard FL, Sorn S, Vong S. Biosecurity measures for backyard poultry in developing countries: a systematic review. *BMC Vet Res.* (2012) 8:240. doi: 10.1186/1746-6148-8-240
41. Conan A, Goutard FL, Holl D, Ra S, Ponsich A, Tarantola A, et al. Cluster randomised trial of the impact of biosecurity measures on poultry health in backyard flocks. *Vet J.* (2013) 198:649–55. doi: 10.1016/j.tvjl.2013.09.010

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Adoption of Secure Pork Supply Plan Biosecurity by U.S. Swine Producers

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There is mounting concern about the negative animal health and supply chain consequences of animal disease outbreaks in the United States. Recent disease outbreaks have drawn attention to the need for additional understanding of biosecurity efforts to reduce disease frequency, spread, and impact. Biosecurity is a key component of the Secure Pork Supply (SPS) Plan designed to provide business continuity in the event of a foreign animal disease outbreak as well as help protect operations from endemic diseases. Core biosecurity recommendations outlined in the SPS Plan are a written site-specific biosecurity plan and implementation of a perimeter buffer area and a line of separation. To-date, no benchmarking of SPS Plan biosecurity implementation has been done. Utilizing data from a 2017 survey of U.S. swine producers, this study shows that SPS Plan biosecurity adoption varies and is affected by how feasible producers believe implementation of each biosecurity practice is on their operation. Furthermore, binomial logit regression analyses indicate producer and operation demographics and producer risk attitudes and perceptions affect biosecurity adoption. Conditional probabilities reveal that adoption of biosecurity practices is overwhelmingly complementary, suggesting that one biosecurity practice likely increases marginal efficacy of another biosecurity practice. The insights this study provides regarding the complexities of biosecurity adoption are vitally important to both educators and policy makers.

Keywords: animal health economics, biosecurity adoption, foreign animal diseases, Secure Pork Supply Plan, pig, swine

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INTRODUCTION

African swine fever (ASF), classical swine fever (CSF), and foot and mouth disease (FMD) are highly contagious transboundary animal diseases. An outbreak of one of these diseases in a country poses a severe threat to animal health and animal agriculture and would have significant economic consequences. Because of their potential for serious and rapid spread irrespective of borders and their ability to cause serious economic consequences and impact trade of animals and animal products, these foreign animal diseases (FADs) are reportable to and monitored by the World Organization for Animal Health (OIE). The United States has maintained ASF-, CSF-, and FMD-free status, but with these diseases present in many other countries, including the unsettling recent global ASF developments, the risk of introduction and spread is at the height of U.S. fears, considerations, and planning.

If ASF, CSF, or FMD were confirmed in the United States, response strategies for controlling and stopping the spread of these animal diseases would likely be far-reaching. It is reasonably certain that as a result of an outbreak of one of these diseases all movement of animals from affected industries would come to a complete halt, as would U.S. meat exports. Depending on the severity of the outbreak and the method used to contain the disease, some markets could remain closed for an extended period of time.

The Secure Pork Supply (SPS) Plan provides opportunities for pork producers through premise identification, enhanced biosecurity implementation, surveillance and sample collection, and movement monitoring to voluntarily prepare before a FAD outbreak. Having the SPS Plan implemented prior to an FAD outbreak is intended to enhance coordination and communication between all stakeholders, speed up a successful FAD response, and eventually enable the issuance of animal movement permits after the extent of the outbreak is understood. Collectively, this should help support continuity of business for participating producers and allied industries[1].

In order for the SPS Plan to effectively meet the goals it has set forth, a minimum level of participation is necessary, and the full benefits of the plan are likely only realized with a high level of participation. To date, no benchmarking of SPS Plan implementation has been done. This highlights a critical need that we aim to meet in this study by identifying and explaining producer implementation of SPS Plan components, namely enhanced biosecurity adoption. Understanding adoption, or lack thereof, is important for improving program targeting and policy deliberations as well as for increasing voluntary participation.

BACKGROUND AND WORK NEEDED

The United States is a significant producer and consumer of pork and pork products, and any event that would interrupt exports, imports, or movement of animals within the country would have serious economic consequences. In 2017, the United States was the world's second-largest exporter of pork and pork products, with exports averaging 22% of domestic commercial pork production (1). Live imports into the United States are important to the domestic swine industry, with imports of all hogs and pigs into the United States during 2017 totaling 5.6 million head (2). Specifically, feeder pig imports from Canada during 2017 accounted for 4.8 million head (2). Internally, U.S. pork production depends on the extensive movement of animals. Of the approximately 171.4 million hogs and pigs marketed in the United States in 2017, 55.2 million were shipped across state lines for feeding or breeding purposes (3). With this being the case, any factor that might restrict exports, imports, and state-to-state shipments would have serious economic implications for producers and the broader economy. Therefore, it is important to identify, prior to an outbreak, potential procedures and plans that may mitigate the consequences and maintain continuity of business by reestablishing movements and trade as quickly as possible.

During a FAD outbreak, as is the case with any other disease, it is a producer's responsibility to keep his/her animals from becoming infected. As such, while the responsibility for preventing the introduction of a FAD into the United States is primarily assigned to the U.S. Department of Agriculture Animal and Plant Health Inspection Service (USDA-APHIS) and other government agencies, producers are the first line of defense in preparedness and are critical to response and recovery efforts. Work on the SPS Plan by federal and state officials, industry, and academia has created recommendations for enhanced biosecurity practices that are designed to prevent the introduction and spread of disease agents onto or off of a production site. The specific practices are crafted based on knowledge about FMD, CSF, and ASF, but they also help protect production sites from endemic diseases (4).

As described by Levis and Baker (5), biosecurity is comprised of bio-exclusion, bio-management, and bio-containment. Bio-exclusion aims to prevent the introduction of a disease into a herd or system, bio-management seeks to minimize the impact of diseases that have already been introduced into a herd or system, and bio-containment strives to prevent the spread of diseases from one herd or system to another, thereby protecting the rest of the supply chain (5). Even though bio-containment would be the most vital of the three components in the event of a FAD outbreak in the United States, this component often receives the least amount of attention from producers (5). The SPS Plan outlines enhanced biosecurity measures that, in addition to reflecting bio-exclusion and bio-management, contribute directly to bio-containment. Adoption of these recommended biosecurity practices would be one component in positioning operations (premises) with animals that have no evidence of infection during the outbreak to move animals to processing or another pork production premises under a movement permit and maintain domestic markets.

The SPS Plan could also help maintain continuity of business because it could be instrumental in compartmentalization and regionalization efforts. According to FAO and OIE (6), compartmentalization and regionalization (also known as zoning) are two disease management strategies that seek, through use of preventative biosecurity practices and separation of animal populations, to distinguish animal populations with differentiable health status. Whereas compartmentalization deals primarily with management and biosecurity within the establishments comprising the compartment, zoning focuses more on natural or human-made barriers and other geographic features (6). The disease-free status of these compartments and zones could promote continuity of business and prevent interruptions to, or reestablish, international trade (7). Compartmentalization has not been fully implemented by the United States for any disease agent to date and will depend on the recognition of the status of these compartments by international trading partners (6), but zoning helped maintain safe trade in poultry and poultry products during the highly pathogenic avian influenza outbreak in the United States in 2015 (8). The enhanced biosecurity measures recommended in the SPS biosecurity guidelines could contribute to compartmentalization (in particular) and zoning as they could aid producers in providing assurances to pertinent officials that they are not contributing to the

[1] For more information refer to the SPS Plan website at http://www.securepork.org/.

spread of disease nor putting their own animals at risk of exposure.

An operation's ability to adopt, implement, and sustain a biosecurity intervention or process such as the SPS Plan is complex. As highlighted by Levis and Baker (5), the use of biosecurity measures differs widely among operations for a wide variety of reasons which include type of swine operation, geographic location, and epidemiological situation, which refers to causes, distribution, and control of diseases in the herd. Moore et al. (9) suggest many potential causes for producers deciding not to implement biosecurity recommendations, among which are an unawareness about the potential risks both to their operation and the entire industry, a miscalculation of costs compared to benefits, and confusion regarding which recommendations to adopt. Complicating the situation even further is, as Hennessy [(10), p. 70] notes, "Prevention involves making resource allocation choices about low probability risks that may materialize in the indefinite future. People are not particularly good at making such decisions, tending to overemphasize some risks and place too much weight on the recent past."

Most data concerning producer decision making regarding biosecurity adoption is often incomplete or lacks the requisite depth for rigorous analysis. Lists of recommended biosecurity practices have been created by various entities (9), but there has been little research on adoption of these recommended biosecurity practices by swine producers in the United States. This makes intuitive sense given that, until the porcine epidemic diarrhea virus (PEDV) outbreak in 2013-14, most pork producers in the United States had not personally experienced a large emerging animal disease outbreak on their operations during their lifetimes, so adoption of biosecurity in U.S. pork production historically has been primarily precautionary and voluntary. This biosecurity paradigm is still generally in place today, but the PEDV outbreak did heighten awareness of new and improved biosecurity that proved beneficial against PEDV and a host of other pathogens and likely led to implementation of more complete and stringently suggested biosecurity plans. Still, existing data are mainly descriptive and lack the depth to fully understand producer decision making.

The literature on biosecurity adoption by swine producers in other countries is more comprehensive likely due to the number and type of animal disease outbreaks and damages incurred as well as both the existence of permit/assurance bonding schemes where it is the owners' responsibility to keep their animals free of disease and livestock disease insurance products available that offer reduced premiums for owners practicing good biosecurity (11). In particular, many studies have addressed livestock biosecurity adoptions in Europe, with recent examples including Simon-Grifé et al. (12) in Spain, Sahlström et al. (13) in Finland, and Postma et al. (14) in Belgium, France, Germany, and Sweden. Some of these studies identify producer and operation characteristics that influence adoption, but there has been little research on such impacts in the United States. Because SPS Plan enhanced biosecurity implementation is precautionary and voluntary, producer perceptions and characteristics of their operations are certainly important drivers of adoption.

The goal of this analysis is to first identify producer views on the feasibility of implementation of SPS Plan enhanced biosecurity recommendations on their operation. Of interest is whether feasibility (i.e., practicality of affordable implementation) may help explain lower-than-expected adoption of recommended biosecurity measures. Second, this analysis seeks to determine what type of producers (and operations) have implemented the SPS Plan enhanced biosecurity guidelines. Knowledge of these characteristics will help program administrators and educators better serve current participants as well as identify the characteristics of producers not currently participating and thus enable more efficient resource allocation in efforts to expand participation. Furthermore, since a biosecurity program is only as good as its weakest point, there is a need to understand what specific practices may increase adoption of other practices. Therefore, we also examine the complementary nature of biosecurity adoption. Altogether, this study provides the first comprehensive analysis of producer participation in the SPS Plan and should be critically valuable in future management of the SPS Plan and related programs.

MATERIALS AND METHODS

Survey Instrument and Data

The survey procedures were approved by the Iowa State University Office for Responsible Research, Institutional Review Board. All methods for data collection and gathering were performed in accordance with the relevant regulations and in compliance with the received guidelines. Completion of the questionnaire by survey participants constituted implied consent.

A questionnaire developed by researchers and extension professionals and administered by the Iowa State University Center for Survey Statistics and Methodology was used in collecting information from swine producers in Iowa, Illinois, Indiana, Kansas, Minnesota, Michigan, Missouri, Nebraska, North Carolina, Ohio, Oklahoma, South Dakota, and Wisconsin. The 13 states surveyed represent 50% of U.S. hog operations and 91% of the U.S. hog inventory (15).

The survey questions were programmed for online application using Qualtrics survey software (Qualtrics, Provo, UT). The sampling frame used in selecting producers to survey was developed from state pork producer association membership lists. Survey data was collected using the online survey mechanism from March 23 through June 1, 2017. Information collected in the survey included producer and operation demographic characteristics, responses to how feasible implementation of SPS Plan biosecurity practices are on a producer's operation, and data detailing producers' use of SPS Plan biosecurity practices. Completed or partially completed surveys from 371 producers were received. **Table 1** reports selected characteristics of the survey respondents. Further details regarding the survey instrument and sample design, data collection procedures, and a comprehensive summary of the data are available in Pudenz et al. (16).

TABLE 1 | Characteristics of survey respondents.

Variable	Description	N	Mean	Std. dev.
AGE	Age of producer (in years)	276	53.366	12.107
COLLEGE	= 1 if 4 year college degree or graduate degree; 0 otherwise	279	0.563	0.497
WHAT OPERATION TYPE BEST DESCRIBES YOUR HOG OPERATION?				
FARROWFINISH	= 1 if farrow to finish; 0 otherwise	371	0.299	0.459
BREEDING	= 1 if breeding/farrowing or nursery; 0 otherwise	371	0.105	0.307
WEANFINISH	= 1 if wean to finish; 0 otherwise	371	0.364	0.482
FINISH	= 1 if finish; 0 otherwise	371	0.173	0.378
OTHEROPERATION	= 1 if boar stud or gilt developer unit or other operation type; 0 otherwise	371	0.059	0.237
WHICH BUSINESS ARRANGEMENT BEST DESCRIBES THE AGREEMENT UNDER WHICH YOU ARE PRESENTLY PRODUCING HOGS?				
INDEPENDENT	= 1 if independent producer; 0 otherwise	369	0.485	0.500
INTEGRATOR	= 1 if contractor or integrator; 0 otherwise	369	0.106	0.308
CONTRACTGROWER	= 1 if contract grower (contractee); 0 otherwise	369	0.360	0.481
OTHERBUSINESS	= 1 if other business arrangement; 0 otherwise	369	0.049	0.216
IOWA	= 1 if Iowa pork producer; 0 otherwise	371	0.604	0.490
PRODUCTIONSITES	Number of separate productions sites (unique premise ID, unique address) in 2016	351	16.436	57.481
HIGHRATING	= 1 if producer's operation biosecurity is perceived to be higher than other operations in the area; 0 otherwise	336	0.830	0.376
REPORTABLE	= 1 if a producer's operation has experienced PRRSV and/or PEDV in the past 3 years; 0 otherwise	354	0.684	0.466
HOW MANY TIMES IN THE NEXT 100 YEARS DO YOU THINK A TIER 1 DISEASE OUTBREAK WILL OCCUR IN THE U.S. SWINE INDUSTRY?				
NOOUTBREAKS	= 1 if no outbreaks expected; 0 otherwise	298	0.091	0.288
ONEOUTBREAK	= 1 if one outbreak expected; 0 otherwise	298	0.235	0.425
TWOOUTBREAKS	= 1 if two or more outbreaks expected; 0 otherwise	298	0.674	0.469

Feasibility and Implementation Cross Tabulation Analysis

The SPS Plan emphasizes biosecurity concepts that all pork production sites must implement to help protect their animals from endemic diseases and to be prepared in the event of an FAD outbreak in the United States. These include a written site-specific plan, perimeter buffer area (PBA), and line of separation (LOS) [2,3].

A self-assessment checklist for meeting PBA and LOS biosecurity performance standards was presented to each survey participant. **Figure 1** provides examples of these survey questions, and the full list of PBA and LOS practices are displayed in **Table 2**. The survey contained Likert scale responses on a scale of 1 to 5 for feasibility of implementation, with 1 labeled as highly infeasible, 2 as infeasible, 3 as neutral, 4 as feasible, and 5 as highly feasible. These numerical responses were converted into categorical variables. Responses 1 and 2 were combined and converted into one infeasible label, 4 and 5 (feasible) were combined, and response 3 was not combined with other responses in order to more directly compare infeasible and feasible responses. Respondents who chose response 3, the neutral choice, might have been those who did not know or have definitive opinions about the feasibility of implementation (17). For questions regarding implementation on a producer's operation, responses were coded as binary variables equal to one if used on an operation and zero otherwise. Cross-tabulations were used to examine relationships between how feasible producers believe implementation is on their operation and if PBA and LOS practices are used on their operation.

Binomial Logit Regression Analysis

Binomial logit regression analysis was used to determine the types of producers and operations most likely to adopt each of the following biosecurity practices: a written site-specific plan, PBA, and LOS. Two models were estimated to determine factors affecting development and implementation of a written site-specific plan, one for a plan for employees and one for a plan for delivery/service personnel. Separate models were estimated for each PBA practice (four total) and for each LOS practice (10 total), resulting in a binomial logit regression being estimated for each biosecurity practice. Descriptions and summary statistics for all 16 dependent variables (i.e., the aforementioned biosecurity practices) are provided in **Table 2**. Explanatory variables derived from the survey data are categorized as producer characteristics, operation characteristics,

[2]These three concepts were outlined in "SPS Plan Update 2013, DRAFT SPS Plan: Appendix A Producer Biosecurity." The 2013 draft expounds on these recommendations, highlighting the importance of a PBA and a LOS (particularly) and listing various components of each. As such, the PBA and LOS are the focus of the feasibility analysis. Since 2013, the SPS Plan has gone through various updates, with the current iteration of the SPS Plan highlighting *four* biosecurity recommendations: the previously-mentioned three items, as well as the explicit recommendation for a designated Biosecurity Manager (4).

[3]The SPS Plan defines a perimeter buffer area (PBA) as an outer control boundary around swine buildings designed to restrict disease transmission near such buildings and a line of separation (LOS) as a control boundary to restrict disease transmission into areas where hogs can be exposed (4). In practice, a PBA is often a fence or other physical barrier with defined access points around swine buildings while a LOS is often the walls of the buildings themselves (4). See Secure Pork Supply [(4), pg. 5] for an illustrative diagram of a PBA and a LOS.

A Perimeter Buffer Area (PBA) functions to keep potentially pathogen contaminated personnel, vehicles, and equipment from contaminating swine production areas. For the PBA practices listed below, please check the left column for those used on your operation. Also for all PBA practices, please indicate by circling a number how feasible you believe implementation of each is on your operation.

X if used	Perimeter Buffer Area	Highly Infeasible	Infeasible	Neutral	Feasible	Highly Feasible
☐	A perimeter buffer area is clearly defined	1	2	3	4	5

A Line of Separation (LOS) provides a physical barrier to prevent pathogen contact between the outside and pigs being housed on a site. A crossing point in the LOS is needed for daily care of pigs and entrance and exit of pigs from the site. For the LOS practices listed below, please check the left column for those used on your operation. Also for all LOS practices, please indicate by circling a number how feasible you believe implementation of each is on your operation.

X if used	Line of Separation	Highly Infeasible	Infeasible	Neutral	Feasible	Highly Feasible
☐	A line of separation is clearly defined for each building	1	2	3	4	5

FIGURE 1 | Example perimeter buffer area and line of separation questions from a 2017 survey of U.S. swine producers.

and risk attitudes. See **Table 1** for descriptions and summary statistics of the explanatory variables.

Several of the explanatory variables require more explanation. Specifically, one novel contribution of this study is inclusion of an operation's past experience with any of the most common prevalent swine diseases. Of the five disease options included in the survey, porcine reproductive and respiratory syndrome (PRRS), and porcine epidemic diarrhea virus (PEDV) were the two diseases appearing on the U.S. National List of Reportable Animal Diseases for 2017 (18). Therefore, to control for past disease experiences, we include *REPORTABLE* as a binary explanatory variable that equals one if the producer had experienced a PRRS and/or PEDV outbreak on their operation in the last 3 years and zero otherwise.

Explaining producers' behavior in risky situations requires characterizations of risk attitudes. Exploratory factor analysis was conducted on responses to five Likert scale questions from the survey to assess swine producers' attitudes toward risk, especially in regards to how they manage their business financially. These questions included: (*a*) When marketing my hogs, I prefer financial certainty to financial uncertainty; (*b*) With respect to the conduct of my business, I prefer certainty to uncertainty; (*c*) I like "playing it safe"; (*d*) I am willing to take higher financial risks in order to realize higher average returns; and, (*e*) I like taking financial risks. The factor analysis (a principal factor analysis with a promax rotation) resulted in two factors that together explained more than 70% of the variation in the responses to the five Likert scale questions. The first factor was named *RISKAVERSE* due to high loadings on the first three questions, while the second factor was named *RISKACCEPTING* due to high loadings on the last two questions. In other words, the *RISKAVERSE* factor makes a meaningful contribution to the variation in responses to questions about risk aversion, while the *RISKACCEPTING* factor contributes meaningfully to the variation in responses to questions about risk acceptance. Scores for each factor, which are the sums of optimally weighted scores on the five questions (19), were estimated for each producer and included in each of the models as explanatory variables.

To account for expectations based on future disease events, a prospective risk attitude explanatory variable describes the number of times in the next 100 years that producers think a Tier 1 disease outbreak will occur in the U.S. swine industry. For this variable, responses were categorized into no outbreaks expected (*NOOUTBREAKS*), one outbreak expected (*ONEOUTBREAK*), and two or more outbreaks expected (*MUTIPLEOUTBREAKS*). This equates to a 0, 1, or 2% or more, respectively, perceived probability of a Tier 1 disease outbreak.

RESULTS AND DISCUSSION

Feasibility of Biosecurity Implementation

Table 2 shows the percentage of producers responding to the survey that implemented each of the four PBA and ten LOS practices. Interestingly, PBA practice implementation was relatively low. Nearly 60% of producers verify all animal transport vehicles being clean, disinfected, and dried before entry to the site, but the remaining practices had mean adoption rates of less than 40%. Adoption of LOS practices was generally higher, however, with two practices having adoption rates above 90%.

Beliefs regarding how feasible implementation of each biosecurity practice is on his/her operation likely influences a producer's motivation to implement, as some measures could be perceived impractical or impossible (20–22). Relationships between feasibility ratings and biosecurity practice implementation were investigated using cross-tabulations (**Table 2**). The values in each of the cells in the table represent the

TABLE 2 | Cross-tabulations of PBA and LOS implementation and feasibility of implementation.

			Mean	Implementation by feasibility rating		
Practice	**Description**	***N***	**Implementation**	**Infeasible**	**Neutral**	**Feasible**
PERIMETER BUFFER AREA (PBA)						
PBADEFINED	A perimeter buffer area is clearly defined	317	0.391 (0.489)	0.161 (0.371)[a]	0.185 (0.391)[a]	0.569 (0.497)[b]
PBAENTRY	Access to perimeter buffer area is restricted through a single entry with a gate at the entrance which is locked when the facility is not attended	317	0.177 (0.382)	0.082 (0.276)[a]	0.117 (0.323)[a]	0.340 (0.476)[b]
PBAEQUIPMENT	All vehicles and equipment (not containing animals) entering the perimeter buffer area are documented to be clean, disinfected, and dried	315	0.229 (0.421)	0.066 (0.249)[a]	0.105 (0.309)[a]	0.479 (0.502)[b]
PBATRANSPORT	All animal transport vehicles are verified clean, disinfected, and dried before entry to the site	315	0.571 (0.496)	0.239 (0.430)[a]	0.233 (0.427)[a]	0.761 (0.427)[b]
LINE OF SEPARATION (LOS)						
LOSDEFINED	A line of separation is clearly defined for each building	309	0.605 (0.490)	0.327 (0.474)[a]	0.180 (0.388)[b]	0.778 (0.417)[c]
LOSLOCKED	Buildings are locked when no one is present	308	0.425 (0.495)	0.123 (0.331)[a]	0.064 (0.247)[a]	0.612 (0.488)[b]
LOSENTRY	One entry point has been established for personnel to cross the line of separation	308	0.688 (0.464)	0.235 (0.428)[a]	0.231 (0.427)[a]	0.876 (0.330)[b]
LOSANIMALS	All animals, including birds, are excluded from crossing the line of separation and contacting pigs	308	0.731 (0.444)	0.233 (0.427)[a]	0.409 (0.503)[b]	0.894 (0.309)[c]
LOSLOG	A visitor logbook is maintained by the site manager/owner	309	0.495 (0.501)	0.314 (0.471)[a]	0.125 (0.334)[b]	0.619 (0.487)[c]
LOSCLOTHING	Employees and visitors are instructed to change into site-specific coveralls or clothing and boots and wash hands when crossing to the pig side of the line of separation	309	0.770 (0.421)	0.361 (0.487)[a]	0.458 (0.509)[a]	0.859 (0.348)[b]
LOSCLOTHESPBA	When a site includes multiple pig buildings, site-specific clothing or coveralls and boots are put on within the perimeter buffer area and boots changed at each barn when crossing the line of separation	296	0.534 (0.500)	0.154 (0.364)[a]	0.190 (0.397)[a]	0.741 (0.439)[b]
LOSFOMITES	All equipment and other objects (including cell phones, jewelry, and electronics) that cross to the pig side of the line of separation are cleaned and disinfected, or come from a known clean source	303	0.419 (0.494)	0.137 (0.346)[a]	0.109 (0.315)[a]	0.663 (0.474)[b]
LOSCLEANING	Cleaning and disinfecting of animal rooms and buildings between groups of pigs is required	304	0.905 (0.294)	0.632 (0.496)[a]	0.313 (0.479)[b]	0.959 (0.198)[c]
LOSFEED	Feed is delivered and stored in bird, rodent, and insect proof containers/bins and feed spills are cleaned up	304	0.901 (0.299)	0.636 (0.492)[a]	0.467 (0.516)[a]	0.948 (0.223)[b]

Standard deviations are in parentheses.
[a,b,c]Values within the same row with unique superscripts differ $P < 0.10$ according to Wilcoxon rank sum tests.

percentage of those in the corresponding feasibility categorical group that have implemented the biosecurity practice. Not surprisingly, producers who believed implementation of a biosecurity practice was infeasible on their operation had lower implementation of that practice than producers who believed implementation was feasible.

For most practices, no statistically significant differences in implementation were detected between producers who believed implementation of a biosecurity practice was infeasible on their operation compared to those who were neutral about the feasibility of implementation. A few exceptions were found for LOS practices. For example, producers who were neutral about the feasibility of a line of separation being clearly defined for each building had a lower level of implementation of this practice than those who believed the practice was infeasible. Conversely, producers who were neutral about the feasibility of excluding all animals, including birds, from crossing the line of separation and contacting pigs had a higher level of implementation than those who believed the practice was infeasible. As previously indicated, a neutral response may indicate not knowing or having a definitive opinion about the feasibility of implementation, which may indicate a lack of knowledge of costs of implementation more generally. For example, fixed costs of biosecurity implementation are often relatively straight forward, but variable costs can be highly variable especially with respect to time (opportunity cost) and labor.

Comparing the relative implementation levels across feasibility ratings reveals several interesting patterns. Some producers are choosing not to implement certain biosecurity practices even though they consider the practices to be feasible to implement on their operation. On the other hand, some producers are choosing to implement biosecurity regardless of whether they deem the practice feasible to implement. This suggests that adoption of biosecurity measures on operations depends not only on feasibility of implementation, but on other motivations such as socio-economic factors.

Determinants of Biosecurity Implementation

To examine the socio-economic factors related to adoption of SPS Plan biosecurity recommendations, we used binomial logit regressions. We focus on the marginal effects (**Tables 3**, **4**) to show statistical significance of results and for interpretations of variables, where marginal effects were calculated as in Greene [(23), p. 734] for continuous variables and Greene [(23), p. 735] for binary variables. The marginal effects indicate the percentage change in probability either at the mean for continuous explanatory variables or for the "1" value for binary explanatory variables. Thus, one should interpret a positive effect as meaning that an increase in that explanatory variable has a positive impact on the probability of adopting the biosecurity practice in question.

Although the marginal effects varied, several patterns emerged across the 16 estimated logit regressions. The signs on the marginal effects vary across biosecurity practices, but where the marginal effects were statistically significant, respondents were more likely to adopt certain practices as age increased. The effect of producer age on biosecurity adoption has provided mixed results in previous related research concerning adoption of other types of practices (24, 25). Older, more experienced swine producers may be expected to recognize the advantages of biosecurity practices, and thus to implement them. At the same time, those who have been in the business longer may be slower to adopt newer biosecurity practices.

Previous research has found that higher education results in greater adoption of technologies, management practices, and production systems (25, 26). However, we find that producers who hold a 4 year college degree were 14.2% less likely to maintain a visitor log book and 7.8% less likely to insure that feed is delivered and stored in bird, rodent, and insect proof containers/bins and feed spills are cleaned up. Although signs on the marginal effects for some other biosecurity practices suggest greater use by college-educated producers, these marginal effects are not statistically significant.

Operation type had a large influence on biosecurity adoption. When compared to farrow to finish operations, finishing operations were 18.8% more likely to always provide site-specific biosecurity procedures to employees and 19.0% more likely to always provide site-specific biosecurity procedures to delivery/service personnel. These results are somewhat unexpected given the health pyramid concept (27), which seeks to minimize the downstream effects of disease by controlling for disease toward the top of the pyramid and thus prioritizes the health of animals in the genetic nucleus and multiplication population, followed by farrowing and gestation, nursery, and lastly finishing animals. On the other hand, farrow to finish operations likely have fewer live animal inputs and retain some attributes of a closed herd which minimizes disease entry and introduction and could conceivably lessen the biosecurity needed. The results concerning breeding (i.e., breeding/farrowing or nursery) operations, however, reflect the health pyramid concept more closely, with breeding operations being more likely to adopt many LOS practices compared to farrow to finish operations. For example, breeding operations were 19.7% more likely to have a defined LOS than farrow to finish operations.

Business arrangement also had a large impact on adoption of biosecurity practices. For example, compared to independent producers, contract growers were more likely to always provide site-specific biosecurity procedures to employees (25.1%) and delivery/service personnel (23.2%). This makes sense considering that the U.S. swine industry is increasingly defined by contracts with growers to manage hogs provided and owned by a contractor. Production contracts typically spell out not only the length of a contract, terms for its renewal, and circumstances that would result in termination, but also specific provisions regarding which party is responsible for inputs like equipment, facilities, feeder pigs, feed, and other terms such as biosecurity policies. As such, the level of biosecurity might be institutionally fixed through production contract agreements.

More production sites as part of an operation was found to have a small but positive impact on biosecurity adoption suggesting the presence of economies of size. For instance, for every 10 additional production sites, a producer was about 0.7% more likely to always provide site-specific biosecurity procedures to employees and to delivery/service personnel and 0.9% more likely to have a defined LOS. This is consistent with Hennessy (28), Bottoms et al. (29), Nöremark et al. (30), and other studies that find larger operations are more likely to adopt biosecurity measures.

The Iowa variable, which represents geographical and pig density differences from other states, was generally found to decrease adoption rates [4]. This seemingly contradicts the results of Bottoms et al. (29), who found that high herd density generally corresponded to higher biosecurity for sow herds in Ontario, Canada. Iowa is the most intensely populated hog production and pork processing state in the U.S. Geographical location of an operation and pig density in the area are two significant factors in the epidemiology of several diseases but, in general, producers do not have much control over them. In high pig density areas, it can be very difficult or impractical to maintain disease freedom from common endemic diseases. This is no excuse for lower biosecurity, but an appreciation of what is realistically achievable is essential and likely leads to mixed results when it comes to biosecurity implementation in high pig density regions.

Incidence of a reportable disease on an operation and high biosecurity self-rating were generally found to encourage biosecurity adoption. For example, compared to producers who

[4] A custom link survey was utilized in Iowa. In an effort to increase survey response, expand distribution to include swine producers from other states, and respective state associations' reticence concerning access to members an open link survey was utilized for swine producers outside of Iowa. As such, we were only able to identify Iowa operations with certainty with producers outside of Iowa not reporting which states(s) their production sites are located in or reporting multiple states. While the Iowa variable does allow us to roughly identify how the use of biosecurity measures differ across geographic location, future research should further explore geographical differences with the inclusion of additional states or regions.

TABLE 3 | Adoption of written site-specific biosecurity plan and perimeter buffer area practices: marginal effects (SE).

Variable	PLAN EMPLOYEES	PLAN PERSONNEL	PBA DEFINED	PBA ENTRY	PBA EQUIPMENT	PBA TRANSPORT
AGE (Δ 1 year)	−0.001 (0.002)	−0.001 (0.002)	0.004* (0.002)	−0.002 (0.002)	0.001 (0.002)	0.007*** (0.002)
COLLEGE	0.010 (0.053)	−0.038 (0.053)	0.027 (0.055)	0.014 (0.042)	−0.034 (0.051)	0.055 (0.058)
BREEDING (vs. FARROWFINISH)	0.064 (0.106)	0.085 (0.105)	−0.019 (0.107)	0.110 (0.097)	0.025 (0.098)	0.053 (0.120)
WEANFINISH (vs. FARROWFINISH)	0.046 (0.068)	−0.021 (0.076)	−0.163** (0.075)	−0.030 (0.063)	−0.130* (0.067)	−0.110 (0.077)
FINISH (vs. FARROWFINISH)	0.188** (0.090)	0.190* (0.106)	−0.040 (0.101)	−0.008 (0.081)	−0.033 (0.090)	−0.077 (0.111)
OTHEROPERATION (vs. FARROWFINISH)	−0.032 (0.136)	0.144 (0.139)	0.016 (0.139)	0.185 (0.130)	0.091 (0.139)	0.069 (0.150)
INTEGRATOR (vs. INDEPENDENT)	0.165 (0.105)	0.232** (0.110)	0.253** (0.118)	0.066 (0.084)	0.184 (0.123)	0.149 (0.118)
CONTRACTGROWER (vs. INDEPENDENT)	0.251*** (0.066)	0.232*** (0.068)	0.170** (0.075)	0.091 (0.060)	0.067 (0.072)	0.044 (0.073)
OTHERBUSINESS (vs. INDEPENDENT)	0.202** (0.103)	0.287** (0.116)	0.151 (0.130)	0.066 (0.103)	0.210 (0.139)	0.247** (0.117)
IOWA	−0.088 (0.063)	−0.038 (0.061)	−0.227*** (0.068)	−0.204*** (0.050)	−0.158*** (0.061)	−0.123* (0.067)
ln(PRODUCTIONSITES)	0.065** (0.027)	0.069*** (0.024)	−0.003 (0.026)	−0.013 (0.018)	−0.030 (0.024)	0.041 (0.028)
HIGHRATING	0.239*** (0.078)	0.321*** (0.062)	0.106 (0.075)	0.106** (0.049)	0.165*** (0.055)	0.203** (0.080)
REPORTABLE	0.002 (0.061)	−0.012 (0.061)	0.045 (0.062)	0.010 (0.045)	0.065 (0.054)	−0.018 (0.066)
RISKAVERSE	0.051* (0.029)	0.034 (0.030)	0.058* (0.032)	0.079*** (0.026)	−0.010 (0.028)	0.025 (0.032)
RISKACCEPTING	0.033 (0.028)	−0.046* (0.028)	0.014 (0.030)	0.055** (0.023)	0.019 (0.027)	0.059* (0.031)
ONEOUTBREAK (vs. NOOUTBREAKS)	−0.115 (0.118)	−0.056 (0.103)	0.162 (0.118)	−0.048 (0.071)	0.107 (0.118)	−0.088 (0.120)
TWOOUTBREAKS (vs. NOOUTBREAKS)	−0.174* (0.104)	−0.038 (0.101)	0.130 (0.093)	0.018 (0.070)	0.092 (0.088)	−0.077 (0.109)
N	263	262	263	262	262	262
Pseudo (McFadden's) R^2	0.216	0.232	0.159	0.279	0.138	0.123
Predicted adoption rate	0.673	0.344	0.335	0.115	0.107	0.660
Actual adoption rate	0.605	0.385	0.395	0.176	0.240	0.580

, **, * indicate statistical significance at $p < 0.10, < 0.05, < 0.01$, respectively.*

did not experience PRRS and/or PEDV in the last 3 years, producers who had experienced at least one of these diseases were 11.0% more likely to instruct employees and visitors to change into site-specific coveralls or clothing and boots and wash hands when crossing to the pig side of the LOS and 11.7% more likely to have feed delivered and store in bird, rodent, and insect proof containers/bins and have feed spills cleaned up. This is consistent with statements made by Schulz and Tonsor (31) who suggest that the 2013-14 U.S. PEDV outbreak could have had the positive externality of encouraging biosecurity implementation. As expected, producers having rated their own biosecurity as high compared to their neighbors were more likely to adopt several of the recommended biosecurity measures. Of note, producers with a high biosecurity self-rating were 32.1% more likely to always provide site-specific biosecurity procedures to delivery/service personnel.

Risk attitudes were found to be significant determinants of biosecurity adoption. Results indicate that risk-averse producers, as determined via their responses to risk eliciting questions, were more likely to adopt the recommended biosecurity practices. Similarly, a risk-accepting attitude was positively correlated with adoption, the one exception being risk-accepting producers were 4.6% less likely to provide written site-specific biosecurity procedures for all delivery/service personnel. In general, these results suggest that regardless of how risky producers are in how they manage their business financially, they understand the importance of biosecurity measures needed on their operations and adopt accordingly.

Some producers may be more willing than others to adopt enhanced biosecurity practices because of the perceived risk of a high-consequence foreign animal diseases occurring. When compared to no expected outbreaks occurring, expecting one outbreak to occur did not statistically significantly impact biosecurity adoption. Producers who expected two or more outbreaks to occur, however, were less likely to adopt two of the recommended biosecurity practices. This latter result suggests a rather pessimistic view of high-consequence foreign animal diseases occurring in the United States could be a deterrent to biosecurity adoption for some producers and for some particular biosecurity practices.

As Mankad (32) highlights, there is a need to incorporate psychological, social and cognitive factors on decision making related to biosecurity and management practices. Our results emphasize the important role of risk attitudes and perceptions in explaining biosecurity adoption behavior which is valuable since studies of the factors leading to the adoption of technology and management practices by producers all too often focus only on the explanatory role of typical producer demographics.

The last two rows of **Tables 3**, **4** report "predicted adoption rate," and "actual adoption rate," which are useful in evaluating the capability of these models to predict biosecurity adoption. The "predicted adoption rate" is the proportion of producers that each binomial logit regression predicted would adopt a particular biosecurity practice, while "actual adoption rate" is the proportion of producers who adopted that practice as recorded in the survey responses. As these statistics demonstrate, the

TABLE 4 | Adoption of line of separation practices: marginal effects (SE).

Variable	LOS DEFINED	LOS LOCKED	LOS ENTRY	LOS ANIMALS	LOS LOG	LOS CLOTHES	LOS CLOTHESPBA	LOS FOMITES	LOS CLEANING	LOS FEED
AGE (Δ 1 year)	−0.004 (0.002)	−0.003 (0.002)	0.001 (0.002)	0.0004 (0.002)	0.00007 (0.002)	−0.001 (0.002)	−0.001 (0.003)	−0.001 (0.002)	0.001 (0.001)	0.001 (0.002)
COLLEGE	0.041 (0.055)	0.060 (0.057)	−0.031 (0.051)	0.010 (0.049)	−0.142*** (0.055)	−0.071 (0.046)	0.052 (0.060)	0.013 (0.057)	0.058 (0.036)	−0.078** (0.039)
BREEDING (vs. FARROWFINISH)	0.197** (0.090)	0.229** (0.112)	0.270*** (0.057)	0.114 (0.079)	0.299*** (0.102)	0.148** (0.075)	0.213** (0.099)	0.251** (0.118)	−0.057 (0.084)	0.053 (0.070)
WEANFINISH (vs. FARROWFINISH)	0.064 (0.071)	0.113 (0.076)	0.055 (0.065)	0.063 (0.060)	0.009 (0.073)	−0.030 (0.057)	0.109 (0.075)	−0.040 (0.077)	0.067* (0.038)	0.120** (0.048)
FINISH (vs. FARROWFINISH)[a]	0.098 (0.096)	0.091 (0.112)	0.011 (0.092)	0.120 (0.074)	0.153 (0.099)	0.079 (0.074)	0.220** (0.095)	0.074 (0.111)	0.080*** (0.031)	
OTHEROPERATION (vs. FARROWFINISH)	0.141 (0.114)	0.293** (0.127)	0.138 (0.090)	0.116 (0.083)	0.067 (0.138)	0.036 (0.097)	0.050 (0.149)	0.123 (0.145)	0.041 (0.051)	0.092** (0.037)
INTEGRATOR (vs. INDEPENDENT)[b]	−0.031 (0.122)	0.119 (0.121)	−0.075 (0.123)	0.119 (0.087)	−0.124 (0.106)	0.028 (0.114)	−0.001 (0.124)	−0.055 (0.107)		
CONTRACTGROWER (vs. INDEPENDENT)	0.134* (0.070)	0.192*** (0.071)	0.126** (0.063)	0.134** (0.061)	0.089 (0.071)	0.073 (0.055)	−0.074 (0.078)	0.071 (0.075)	0.095*** (0.036)	0.043 (0.059)
OTHERBUSINESS (vs. INDEPENDENT)[b]	0.181 (0.121)	0.364*** (0.120)	0.123 (0.119)	0.110 (0.102)	0.105 (0.140)	0.111 (0.100)	0.082 (0.147)	0.108 (0.142)		
IOWA	0.013 (0.063)	0.021 (0.063)	0.085 (0.058)	0.056 (0.058)	−0.151** (0.064)	−0.045 (0.052)	0.097 (0.068)	−0.172** (0.068)	−0.069* (0.036)	−0.004 (0.048)
ln (PRODUCTIONSITES)	0.089*** (0.028)	0.078*** (0.027)	0.116*** (0.026)	0.086*** (0.027)	0.109*** (0.026)	0.064** (0.026)	0.040 (0.029)	0.039 (0.026)	0.060*** (0.024)	0.007 (0.022)
HIGHRATING	0.264*** (0.080)	0.081 (0.077)	0.227*** (0.074)	0.224*** (0.077)	0.159** (0.077)	0.182*** (0.068)	0.274*** (0.079)	0.211*** (0.074)	0.217*** (0.061)	0.236*** (0.076)
REPORTABLE	0.056 (0.065)	0.102 (0.066)	0.094 (0.060)	0.063 (0.058)	0.068 (0.063)	0.110* (0.057)	−0.007 (0.070)	−0.001 (0.066)	0.028 (0.040)	0.117** (0.058)
RISKAVERSE	0.070** (0.030)	0.045 (0.032)	0.015 (0.028)	0.057** (0.027)	0.057* (0.031)	0.076*** (0.024)	0.059* (0.033)	0.042 (0.032)	0.002 (0.019)	0.034 (0.023)
RISKACCEPTING	0.017 (0.030)	0.014 (0.030)	0.016 (0.027)	0.086*** (0.025)	−0.009 (0.029)	0.034 (0.024)	0.087*** (0.031)	0.051* (0.031)	0.032* (0.018)	0.055** (0.024)
ONEOUTBREAK (vs. NOOUTBREAKS)	0.019 (0.110)	−0.081 (0.108)	−0.065 (0.122)	−0.009 (0.101)	−0.147 (0.103)	−0.040 (0.110)	0.00006 (0.122)	−0.108 (0.104)	0.039 (0.058)	0.064 (0.059)
TWOOUTBREAKS (vs. NOOUTBREAKS)	0.069 (0.104)	−0.062 (0.107)	−0.122 (0.096)	0.051 (0.097)	−0.172* (0.102)	−0.053 (0.091)	−0.042 (0.113)	−0.103 (0.106)	−0.004 (0.057)	0.070 (0.085)
N	263	263	263	263	263	263	260	263	226	199
Pseudo (McFadden's) R^2	0.166	0.143	0.202	0.205	0.215	0.242	0.097	0.141	0.432	0.320
Predicted adoption rate	0.719	0.304	0.791	0.859	0.479	0.878	0.604	0.342	0.951	0.950
Actual adoption rate	0.620	0.414	0.703	0.745	0.498	0.787	0.531	0.411	0.903	0.884

, **, * indicate statistical significance at $p < 0.10$, < 0.05, < 0.01, respectively.*
[a]*Dropped from the regression due to no variation for LOSFEED.*
[b]*Dropped from the regression due to no variation for LOSCLEANING and LOSFEED.*

models reasonably predicted the adoption rate in most cases. In particular, 60.5% of producers always provide site-specific biosecurity procedures to employees, and the model predicted 67.3% of producers would adopt this practice. Results such as these lend credence to the logit procedure used in this analysis. That said, not all of the 16 models performed this well. Additionally, some variables are statistically significant in some models but not in others when we might expect the impact of a variable on adoption to be similar for some (or even most) practices. The results from the logit regressions (and the previously discussed feasibility analysis) indicate that socio-economic factors (producer and operation demographics and producer attitudes and perceptions) play a significant role in biosecurity adoption, but still other factors could be drivers of adoption.

Complementarity of Biosecurity Practices

Thus far, adoption of biosecurity practices have been considered independently. The complementary nature of adoption of the enhanced biosecurity practices could be evaluated to reveal how adoption of one practice influences adoption of another practice. An analysis of complementarity was completed utilizing conditional probabilities (33, 34), with complementarity of adoption being demonstrated by following Chihara and Hesterberg (35) to show statistically significant differences between adoption rates of one practice for adopters and non-adopters of a second practice. Results are reported in **Tables 5–7**.

Consider the following two LOS practices—clearly defining a LOS for each building (*LOSDEFINED*), and having one established entry point for personnel to cross the line of separation (*LOSENTRY*). Intuitively, having a clearly defined LOS is basically required for having one entry point for crossing, so one could reasonably expect that adoption of one of these practices impacts the adoption of the other. The data corroborates this prediction. As shown in **Table 7**, of the subset of producers who reported having a defined LOS, 91.1% reported also having one entry point for crossing. Compare this to the subset of producers who reported not having a defined LOS, of which only 33.6% reported having one entry point for crossing. As expected, adoption of these two biosecurity practices goes hand in hand, and this result is not unique. Consider two other practices for which adoption could be expected to be related—vehicles and equipment entering the PBA are verified to be clean, disinfected, and dried before entry to the site (*PBAEQUIPMENT*), and transport vehicles entering the PBA are verified to be clean, disinfected, and dried before entry to the site (*PBATRANSPORT*). As **Table 6** shows, the conditional probability of verifying that vehicles and equipment entering the PBA are clean, disinfected, and dried given that all transport vehicles entering the PBA are verified to be clean, disinfected, and dried is six times higher (36.8 vs. 5.8%) than the conditional probability of verifying that vehicles and equipment entering the PBA are clean, disinfected, and dried given that the practice of verifying that all transport vehicles entering the PBA are clean, disinfected and dried has not been adopted. Once again, adoption of one of these practices clearly impacts the adoption of the other.

High degrees of complementarity are more or less universal across all practices, even for practices that are not as obviously related as the pairs of practices detailed in the previous paragraph. Consider this time the practices of always providing site-specific biosecurity procedures to both employees and delivery/service personnel (*PLANPROVIDED*) and of clearly defining a PBA (*PBADEFINED*). Even though there is no evident relationship between the two practices, the subset of producers who always provide site-specific biosecurity procedures has a 63.3% adoption rate for clearly defining a PBA, while the subset of producers who do not always provide site-specific biosecurity procedures has a much lower adoption rate of 26.5% for defining a PBA (**Table 5**).

TABLE 5 | Adoption rates of providing a written site-specific biosecurity plan, a defined perimeter buffer area, and a defined line of separation (in italics) given non-adoption or adoption of the other practices (in bold).

	Non-Adoption (%)	Adoption (%)
PLANPROVIDED*		
PBADEFINED	26.5	63.3
LOSDEFINED	52.0	75.0
PBADEFINED		
*PLANPROVIDED**	22.7	58.5
LOSDEFINED	49.2	77.6
LOSDEFINED		
*PLANPROVIDED**	23.2	45.5
PBADEFINED	22.2	50.5

Adoption of PLANPROVIDED means that a producer always provides site-specific procedures to all employees and to all deliver/service personnel. Of the 337 respondents, 37.09% adopted PLANPROVIDED.

All differences (rate given adoption – rate given non-adoption) statistically significant at $p \leq 0.01$.

TABLE 6 | Adoption rates of perimeter buffer area practices (in italics) given non-adoption or adoption of the other perimeter buffer area practices (in bold).

	Non-Adoption (%)	Adoption (%)
PBADEFINED		
PBAENTRY	7.7	32.3
PBAEQUIPMENT	11.3	41.5
PBATRANSPORT	43.6	78.3
PBAENTRY		
PBADEFINED	32.8	73.7
PBAEQUIPMENT	16.8	55.4
PBATRANSPORT	53.0	78.6
PBAEQUIPMENT		
PBADEFINED	30.6	71.1
PBAENTRY	10.1	40.8
PBATRANSPORT	47.4	89.5
PBATRANSPORT		
PBADEFINED	20.3	54.3
PBAENTRY	8.7	23.7
PBAEQUIPMENT	5.8	36.8

All differences (rate given adoption – rate given non-adoption) statistically significant at $p \leq 0.01$.

TABLE 7 | Adoption rates of line of separation practices (in italics) given non-adoption or adoption of the other line of separation practices (in bold).

	Non-adoption (%)	Adoption (%)
LOSCLEANING		
LOSDEFINED	17.2	65.0
LOSLOCKED	10.3	45.9
LOSENTRY	20.7	73.4
LOSANIMALS	17.2	79.1
LOSLOG	10.3	53.4
LOSCLOTHING	24.1	82.7
LOSCLOTHINGPBA	14.3	56.9
LOSFOMITES	10.3	44.7
LOSFEED	51.7	94.0
LOSDEFINED		
LOSLOCKED	18.3	57.8
LOSENTRY	33.6	91.1
LOSANIMALS	48.8	89.1
LOSLOG	27.0	63.5
LOSCLOTHING	53.2	92.2
LOSCLOTHINGPBA	28.9	68.9
LOSFOMITES	12.3	60.3
LOSCLEANING	80.5	97.4
LOSFEED	79.7	96.8
LOSENTRY		
LOSDEFINED	17.0	80.6
LOSLOCKED	13.0	55.0
LOSANIMALS	36.4	89.9
LOSLOG	25.0	60.4
LOSCLOTHING	49.0	89.4
LOSCLOTHINGPBA	25.0	65.9
LOSFOMITES	13.3	54.5
LOSCLEANING	76.5	97.2
LOSFEED	74.5	97.2
LOSANIMALS		
LOSDEFINED	24.7	73.7
LOSLOCKED	16.5	51.7
LOSENTRY	25.9	84.4
LOSLOG	22.4	58.6
LOSCLOTHING	42.4	89.2
LOSCLOTHINGPBA	20.3	64.7
LOSFOMITES	15.7	50.7
LOSCLEANING	71.1	97.8
LOSFEED	69.9	97.4
LOSCLOTHING		
LOSDEFINED	20.3	72.5
LOSLOCKED	13.5	50.8
LOSENTRY	31.1	79.8
LOSANIMALS	33.8	85.2
LOSLOG	8.1	61.5
LOSCLOTHINGPBA	23.2	61.7
LOSFOMITES	11.3	50.4
LOSCLEANING	69.0	97.1
LOSFEED	73.2	95.0

(Continued)

TABLE 7 | Continued

	Non-adoption (%)	Adoption (%)
LOSFEED		
LOSDEFINED	19.4	65.1
LOSLOCKED	12.9	45.9
LOSENTRY	19.4	73.9
LOSANIMALS	19.4	79.3
LOSLOG	9.7	53.7
LOSCLOTHING	38.7	81.5
LOSCLOTHINGPBA	16.1	57.1
LOSFOMITES	12.9	44.6
LOSCLEANING	54.8	94.7
LOSFOMITES		
LOSDEFINED	41.2	88.4
LOSLOCKED	30.2	59.7
LOSENTRY	53.3	89.9
LOSANIMALS	61.5	89.8
LOSLOG	29.7	77.5
LOSCLOTHING	65.4	93.8
LOSCLOTHINGPBA	37.4	75.2
LOSCLEANING	85.7	97.7
LOSFEED	85.2	96.9
LOSCLOTHINGPBA		
LOSDEFINED	39.9	78.3
LOSLOCKED	32.2	51.6
LOSENTRY	49.7	85.1
LOSANIMALS	55.6	90.1
LOSLOG	35.0	62.7
LOSCLOTHING	62.9	90.1
LOSFOMITES	21.7	58.4
LOSCLEANING	83.2	97.5
LOSFEED	81.8	96.9
LOSLOG		
LOSDEFINED	43.2	78.2
LOSLOCKED	30.9	53.8
LOSENTRY	53.4	84.0
LOSANIMALS	59.3	87.7
LOSCLOTHING	58.0	96.2
LOSCLOTHINGPBA	39.2	66.9
LOSFOMITES	18.5	64.9
LOSCLEANING	83.5	98.1
LOSFEED	82.3	98.1
LOSLOCKED		
LOSDEFINED	44.0	82.8
LOSENTRY	53.0	90.2
LOSANIMALS	61.2	89.6
LOSLOG	39.1	62.7
LOSCLOTHING	65.2	92.5
LOSCLOTHINGPBA	44.6	64.3
LOSFOMITES	29.1	58.3
LOSCLEANING	85.5	97.7
LOSFEED	84.9	97.0

All differences (rate given adoption – rate given non-adoption) statistically significant at $p \leq 0.01$.

It is possible that complementarity occurs because the use of one practice increases the marginal efficacy of another practice. However, as Pruitt et al. (33) indicate, it could also be because some people are simply "adopters" of practices. In either case, the complementarity results show that adoption of specific biosecurity practices often go hand in hand.

CONCLUSION

Given that biosecurity adoption in the past in the United States has largely been precautionary and voluntary, this study provides key insights into the very complex and ever-changing issue of biosecurity adoption. Producer attitudes about feasibility of implementation, producer and operation demographics, risk attitudes and perceptions, and complementarity of practices were all shown to play a meaningful role in whether or not a producer adopted recommended SPS Plan biosecurity practices. As was demonstrated, not one of these factors provides the entire picture by itself and there are many factors at play when producers weigh biosecurity adoption. Further complicating the situation is that biosecurity adoption is not static. In fact, producer attitudes and adoption rates may have meaningfully changed since the data for this study was collected, especially in response to the recent outbreaks of ASF in China.

Keeping these complexities in mind is of utmost importance, especially at a time when, for better or for worse, the precautionary and voluntary biosecurity paradigm in the United States appears to be shifting. For example, governing bodies in the United States have not historically mandated (either directly or indirectly) biosecurity adoption in response to concerns with antimicrobial resistance the same way their European counterparts have [see European Commission, (36)]. In recent years, however, policies such as the Veterinary Feed Directive—which has been shown by Schulz and Rademacher (37) to cause producers to modify biosecurity—are being considered and implemented by U.S. governing bodies. As another example, during the 2014–2015 Highly Pathogenic Avian Influenza outbreak in the U.S., indemnity payments to producers were made conditionally on producers providing evidence that they were using biosecurity meant to prevent the spread of the disease when it was discovered in their flocks (38). Given the complicated nature of this issue, this study could provide educators and policy makers with vital information as they think about such policies going forward.

The complexity of this issue also means there are plenty of opportunities for further research. In our survey, producers indicated if they used the recommended biosecurity practices on their operation. Future surveys should consider framing of the question with respect to peacetime (i.e., a normal operating environment) and during an animal health emergency (i.e., acute animal health crisis actively impacting interstate and international trade). That is, instead of presenting binary options "being used" or "not being used," perhaps producers could be asked to select from "being used," "not currently being used but could be if needed," or "not feasible to implement." This approach would help, in part, determine producers' evaluations of industry-wide costs of not adopting biosecurity. Livestock operations obviously have a strong interest in remaining disease-free for a variety of reasons, but operations may not take into account how their actions affect other operations. If a producer is shown to always use a practice, it may be that the producer has a better understanding (or higher valuation) of industry-wide costs of a disease outbreak compared to a producer who only implements biosecurity during an outbreak. Knowing how many producers undervalue industry-wide costs of an outbreak would be very helpful to program administrators and educators.

Future work should also consider collecting information on farm-level costs of biosecurity implementation as this may help to better explain adoption than, more generally, self-assessments of the perceived feasibility of adoption on an operation. For example, biosecurity investments entail a mixture of fixed and variable costs. By knowing farm-level fixed and variable cost estimates, economic tradeoffs could be considered and the relative influence of each for biosecurity adoption identified. Furthermore, knowing costs would help inform cost-sharing schemes related to animal disease mitigation efforts, where biosecurity is intended to be a factor in the cost-sharing strategies.

The logit and complementarity analyses conducted here, although robust, have limitations. In particular, while the complementarity analysis definitely demonstrates that adoption of practices go together, one has to be careful when drawing conclusions about causality when only considering conditional probabilities. Multinomial or multivariate logit models could be used instead of binomial logit models and conditional probabilities, but as Pruitt et al. (33) also found, such analysis is made difficult by the sheer number (in this case, 16) of recommended practices. Also of note is that this analysis is agnostic about the relative importance of different practices. For example, clearly defining a LOS for each building may or may not be more important for overall biosecurity than maintaining a visitor logbook, but the analysis in this study makes no value judgment. Making an assumption about the relative importance of practices could allow for further analysis to proceed. By weighting each practice the same for overall operation biosecurity, one could conduct a count data regression analysis as in Gale (39) to look for jointness in adoption. Alternatively, a weighting system could be applied such as in Postma et al. (14) to give an overall biosecurity rating to each producer before performing subsequent analysis. Future research avenues such as these could enhance and extend the results in this study, providing additional valuable insights about biosecurity adoption.

Future producer and industry leader education efforts may be more targeted by incorporating findings from this study. These refined efforts may lead to a clearer understanding by producers of biosecurity's many decisions and ultimately improved decision-making regarding biosecurity adoption and compliance efforts. Similarly, future efforts to develop new technologies, programs, or protocols to enhance individual firm and industry-wide biosecurity should heed these results. Development or marketing of biosecurity options that producers are unlikely to widely implement is a missed opportunity, while alternatively focusing efforts on options more likely to be utilized is an improved possibility if the results from this study are properly leveraged.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of The Belmont Report: Ethical Principles and Guidelines for the Protection of Human Subjects of Research or other appropriate ethical standards recognized by federal departments and agencies that have adopted the Federal Policy for the Protection of Human Subjects. The protocol was approved by the Iowa State University Institutional Review Board. All methods for data collection and gathering were performed in accordance with the relevant regulations and in compliance with the received guidelines.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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REFERENCES

1. United States Department of Agriculture: Foreign Agricultural Service, Office of Global Analysis (USDA-FAS-OGA). *Livestock and Poultry: World Markets and Trade*. FAS (2018). Available online at: https://apps.fas.usda.gov/psdonline/app/index.html#/app/downloads (accessed September 16, 2018).
2. United States Department of Agriculture: Economic Research Service (USDA-ERS). *Hogs: Annual and Cumulative Year-to-Date U.S. Trade - All Years and Countries*. ERS (2018). Available online at: https://www.ers.usda.gov/data-products/livestock-and-meat-international-trade-data/ (accessed September 16, 2018).
3. United States Department of Agriculture: National Agricultural Statistics Service (USDA-NASS). *Meat Animals Production, Disposition, and Income 2017 Summary*. NASS (2018). Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/02870v85d/tb09j8383/jd473006x/MeatAnimPr-04-26-2018.pdf (accessed April 5, 2019).
4. Secure Pork Supply (2018). *U.S. Pork Industry Guide to the Secure Pork Supply Plan*. Available online at: http://www.securepork.org/Resources/SPS-Booklet-2018.pdf (accessed April 5, 2019).
5. Levis DG, Baker RB. Biosecurity of pigs and farm security. In: *The Board of Regents of the University of Nebraska*. (2011). Available online at: http://extensionpublications.unl.edu/assets/pdf/ec289.pdf (accessed April 5, 2019).
6. Food and Agriculture Organization of the United Nations/World Organisation for Animal Health/World Bank (FAO and OIE). Good practices for biosecurity in the pig sector – Issues and options in developing and transition countries. In: *FAO Animal Production and Health Paper No. 169*. Rome: FAO (2010). Available online at: http://www.fao.org/docrep/012/i1435e/i1435e00.pdf (accessed April 5, 2019).
7. United States Department of Agriculture: Animal and Plant Health Inspection Service, Veterinary Services (USDA-APHIS-VS). *Foot-and-Mouth Disease Response Plan: The Red Book*. APHIS (2014). Available online at: https://www.aphis.usda.gov/animal_health/emergency_management/downloads/fmd_responseplan.pdf (accessed September 16, 2018).
8. Swayne DE, Hill RE, Clifford J. Safe application of regionalization for trade in poultry and poultry products during highly pathogenic avian influenza outbreaks in the USA. *Avian Pathol*. (2017) 46:125–30. doi: 10.1080/03079457.2016.1257775
9. Moore DA, Merryman ML, Hartman ML, Klingborg DJ. Special report: comparison of published recommendations regarding biosecurity practices for various production animal species and classes. *JAVMA*. (2008) 233:249–56. doi: 10.2460/javma.233.2.249
10. Hennessy DA. Economic aspects of agricultural and food biosecurity. *Biosecur Bioterror. Biodef Strateg Pract Sci*. (2008) 6:66–77. doi: 10.1089/bsp.2007.0016
11. Ott S. Issues Associated with US Livestock Disease Compensation in the 21st Century. In: Koontz SR, Hoag DL, Thilmany DD, Green JW, Grannis JL editors. *The Economics of Livestock Disease Insurance: Concepts Issues and International Case Studies*. Cambridge, MA: CABI Publishing (2006). p. 39–52.
12. Simon-Grifé M, Martín-Valls GE, Vilar MJ, García-Bocanegra I, Martína M, Mateua E, et al. Biosecurity practices in Spanish pig herds: perceptions of farmers and veterinarians of the most important biosecurity measures. *J Prev Vet Med*. (2013) 110:223–31. doi: 10.1016/j.prevetmed.2012.11.028
13. Sahlström L, Virtanen T, Kyyrö J, Lyytikäinen T. Biosecurity on Finnish cattle, pig and sheep farms – results from a questionnaire. *J Prev Vet Med*. (2014) 117:59–67. doi: 10.1016/j.prevetmed.2014.07.004
14. Postma M, Backhans A, Collineau L, Loesken S, Sjölund M, Belloc C, et al. The biosecurity status and its associations with production and management characteristics in farrow-to-finish pig herds. *Animal*. (2016) 10:478–89. doi: 10.1017/S1751731115002487
15. United States Department of Agriculture: National Agricultural Statistics Service (USDA-NASS). *2012 Census of Agriculture, United States Summary and State Data*. NASS (2014). Available online at: https://www.nass.usda.gov/Publications/AgCensus/2012/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf (accessed September 16, 2018).
16. Pudenz CC, Schulz LL, Tonsor GT. *Biosecurity and Health Management by U.S. Pork Producers: 2017 Survey Summary*. Iowa State University Extension and Outreach IPIC0105 (2017). Available online at: https://store.extension.iastate.edu/product/Biosecurity-and-Health-Management-by-US-Pork-Producers-2017-Survey-Summary (accessed September 16, 2018).
17. Ryan C, Garland R. The use of a specific non-response option on Likert-type scales. *Tour Manag*. (1999) 20:107–13. doi: 10.1016/S0261-5177(98)00096-X
18. United States Department of Agriculture: Animal and Plant Health Inspection Service (USDA-APHIS). *2017 NLRAD-NAHRS Reportable Disease List*. APHIS (2017). Available online at: https://www.aphis.usda.gov/animal_health/nahrs/downloads/2017_nahrs_dz_list.pdf (accessed September 16, 2018).
19. O'Rourke N, Hatcher L. *A Step-by-Step Approach to Using SAS® for Factor Analysis and Structural Equation Modeling*, *2nd Edn*. Cary, NC: SAS Institute Inc. (2013).
20. Alarcon P, Wieland B, Mateus ALP, Dewberry C. Pig farmers' perceptions, attitudes, influences and management of information in the decision-making process for disease control. *J Prev Vet Med*. (2014) 116:223–42. doi: 10.1016/j.prevetmed.2013.08.004

21. Postma M, Stärk KDC, Sjölund M, Backhans A, Beilage EG, Lösken S, et al. Alternatives to the use of antimicrobial agents in pig production: a multi-country expert-ranking of perceived effectiveness, feasibility and return on investment. *J Prev Vet Med.* (2015) 118:457–66. doi: 10.1016/j.prevetmed.2015.01.010
22. Wu Q, Schulz LL, Tonsor GT, Smith JM. Expert views on effectiveness, feasibility, and implementation of biosecurity measures for mitigating tier 1 disease risks in the U.S. swine, beef cattle, and dairy industries. *J. Vet. Sci. Technol.* (2017) 8:435. doi: 10.4172/2157-7579.1000435
23. Greene WH. *Econometric Analysis*. 6th ed. New York, NY: Pearson (2018).
24. Gillespie J, Kim S, Paudel K. Why don't producers adopt best management practices? An analysis of the beef cattle industry. *Agric Econ.* (2007) 36:89–102. doi: 10.1111/j.1574-0862.2007.00179.x
25. Ward CE, Vestal MK, Doye DG, Lalman DL. Factors affecting adoption of cow-calf production practices in Oklahoma. *J Agric Appl Econ.* (2008) 40:851–63. doi: 10.1017/S1074070800002376
26. Wozniak GD. The adoption of interrelated innovations: a human capital approach. *Rev Econ Stat.* (1984) 66:70–9. doi: 10.2307/1924697
27. Ramirez A, Zaabel P. *Swine Biological Risk Management. Center for Food Security and Public Health*. Iowa State University (2012). Available online at: http://www.cfsph.iastate.edu/pdf/swine-biological-risk-management (accessed April 5, 2019).
28. Hennessy DA. Economies of feedlot scale, biosecurity, investment, and endemic livestock disease. In: *CARD Working Paper 06-WP 433*. (2006). Available online at: http://lib.dr.iastate.edu/card_workingpapers/446 (accessed April 5, 2019).
29. Bottoms K, Poljak Z, Dewey C, Deardon R, Holtkamp D, Friendship R. Evaluation of external biosecurity practices on southern Ontario sow farms. *J. Prev. Vet. Med.* (2013) 109:58–68. doi: 10.1016/j.prevetmed.2012.08.013
30. Nöremark M, Frössling J, Lewerin SS. Application of routines that contribute to on-farm biosecurity as reported by Swedish livestock farmers. *Transbound Emerg Dis.* (2010) 57:225–36. doi: 10.1111/j.1865-1682.2010.01140.x
31. Schulz LL, Tonsor GT. Assessment of the economic impacts of porcine epidemic diarrhea virus in the United States. *J Anim Sci.* (2015) 95:5111–8. doi: 10.2527/jas.2015-9136
32. Mankad A. Psychological influences on biosecurity control and farmer decision-making. A review. *Agron Sustain Dev.* (2016) 36:40. doi: 10.1007/s13593-016-0375-9
33. Pruitt JR, Gillespie JM, Nehring RF, Quishim B. Adoption of technology, management practices, and production systems by U.S. beef cow-calf producers. *J Agric Appl Econ.* (2012) 44:203–22. doi: 10.1017/S1074070800000274
34. Khanal A, Gillespie JM, MacDonald J. Adoption of technology, management practices, and production systems in U.S. milk production. *J Dairy Sci.* (2010) 93:6012–22. doi: 10.3168/jds.2010-3425
35. Chihara L, Hesterberg T. *Mathematical Statistics with Resampling and R, 1st Edn*. Hoboken, NJ: John Wiley & Sons, Inc. (2011).
36. European Commission. *Action Plan Against the Rising Threats From Antimicrobial Resistance*. COM (2011) 748. (2011). Available online at: http://ec.europa.eu/transparency/regdoc/rep/1/2011/EN/1-2011-748-EN-F1-1.Pdf (accessed October 30, 2018).
37. Schulz LL, Rademacher CJ. Food and drug administration guidance 209 and 213 and veterinary feed directive regulations regarding antibiotic use in livestock: a survey of preparation and anticipated impacts in the swine industry. *J. Swine Health and Production*. (2017) 25:247–55.Available online at: https://www.aasv.org/shap/issues/v25n5/v25n5p247.pdf (accessed October 30, 2018).
38. United States Department of Agriculture: Animal and Plant Health Inspection Service (USDA-APHIS). Conditions for Payment of Highly Pathogenic Avian Influenza Indemnity Claims. In: *Federal Register Vol. 81, No. 26.* (2016). Available online at: https://www.gpo.gov/fdsys/pkg/FR-2016-02-09/pdf/2016-02530.pdf (accessed April 5, 2019).
39. Gale HF. Rural manufacturing on the crest of the wave: a count data analysis of technology use. *Am J Agric Econ.* (1998) 80:347–59. doi: 10.2307/1244507

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Willingness to Comply With Biosecurity in Livestock Facilities: Evidence From Experimental Simulations

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Disease in U.S. animal livestock industries annually costs over a billion dollars. Adoption and compliance with biosecurity practices is necessary to successfully reduce the risk of disease introduction or spread. Yet, a variety of human behaviors, such as the urge to minimize time costs, may induce non-compliance with biosecurity practices. Utilizing a "serious gaming" approach, we examine how information about infection risk impacts compliance with biosecurity practices. We sought to understand how simulated environments affected compliance behavior with treatments that varied using three factors: (1) the risk of acquiring an infection, (2) the delivery method of the infection risk message (numerical, linguistic and graphical), and (3) the certainty of the infection risk information. Here we show that compliance is influenced by message delivery methodology, with numeric, linguistic, and graphical messages showing increasing efficacy, respectively. Moreover, increased situational uncertainty and increased risk were correlated with increases in compliance behavior. These results provide insight toward developing messages that are more effective and provide tools that will allow managers of livestock facilities and policy makers to nudge behavior toward more disease resilient systems via greater compliance with biosecurity practices.

Keywords: biosecurity, compliance, risk, uncertainty, graphical message, linguistic phrase, numeric message, psychological distance

INTRODUCTION

Livestock diseases threaten animal welfare and livelihoods throughout production networks. Yet, due to the continued consolidation of livestock production (1, 2), increased movements of animals (3), and globalization of trade within livestock industries (4), disease prevalence is growing. For example, Porcine Epidemic Diarrhea virus (PEDv) was first detected in the U.S. in 2013 and within 12 months this disease had spread to 33 states. Nearly half of hog facilities have experienced a PEDv outbreak since its introduction (5) with net annual economic welfare reductions initially estimated at between $900 million to $1.8 billion (6). Many industry experts agree that implementing biosecurity practices is key to reducing the social and economic impacts of livestock diseases to industry stakeholder and consumers of hog products (7, 8), yet investment in biosecurity is low (9–11). Finding innovative and cost-effective ways to motivate, or nudge, farms to implement and comply with biosecurity practices will be instrumental in protecting livestock herds from endemic, exotic, and emerging diseases.

Biosecurity implementation at livestock facilities is both a tactical decision, with facility managers deciding which preventive biosecurity practices to adopt, as well as a series of ongoing operational decisions, with personnel deciding to comply or not comply with biosecurity practices (12). Regular compliance with biosecurity practices can significantly reduce disease. Unfortunately, many behaviors and signals in the work environment can negatively affect compliance. Behaviors such as habits, complacency, and the urge to minimize expenditures of time may induce non-compliance with biosecurity practices. For example, Beloeil et al. (13) found that consistently changing clothes before entering a hog facility reduced *Salmonella* seropositive animals from 87 to 13%. Yet studies have shown consistency in compliance with these practices is rarely the case (14). Racicot et al. (15), using hidden cameras, found 44 different biosecurity lapses made by workers and visitors at Quebec poultry farms over the course of 4 weeks, with the average number of biosecurity breaches being four per visit (15). The factors involved in this human behavioral dimension of biosecurity implementation are not well-known, but are thought to be essential to biosecurity practices and livestock welfare (16).

In this study we examine factors that may influence perception of disease risk and thus, compliance with biosecurity practices associated with production facilities. Variables to be treated in this study include: information regarding disease infection risk, amount of uncertainty associated with the information provided about the disease infection risk, and the types of message delivery methods used to communicate disease infection risk. These factors have been identified as influencing biosecurity in a variety of livestock systems (8, 17). Risk of disease is ubiquitous in livestock production facilities, but the level of risk at any given time is generally not known since it is challenging to quantify, and the sharing of information about disease prevalence and location is not standard procedure. Risk tolerance is generally high among U.S. farmers (18), but as the actual risk of disease infection is perceived to increase, farmers may be more apt to implement biosecurity or comply with biosecurity protocols (8, 19–21).

The degree of certainty provided in the infection risk message is also expected to affect biosecurity compliance. Ritter et al. (8) suggested that as certainty about disease information is enhanced (and uncertainty reduced), the benefits of practicing biosecurity are presented with greater certainty (19) or salience (22). This could lead to increased biosecurity implementation. Indeed, Merrill et al. (21) found, in an experimental simulation of disease in a swine production region, that a decrease in uncertainty (e.g., increase in certainty) about disease in a simulated swine production system was associated with increased tactical investments in biosecurity.

In addition to infection risk certainty, another important factor may be the perceived reliability of the information, which may vary depending on who is delivering it, consistency of messaging, and the mode of delivery (8, 16). Farmers in Ireland, for instance, received different information from veterinary practitioners vs. dairy advisors, and this perceived inconsistency or unreliability was stated as the primary reason for not implementing biosecurity, even while 83% of the farmers surveyed stated they would adopt practices if that would result in better herd health (23).

Another factor affecting compliance with biosecurity practices is the types of messages that workers at production facilities receive about disease, including the message delivery format. Evidence suggests that using impactful imagery should be more effective than using a number or phrase to convey messages (24). For example, since 1974 the U.S. government has used a rating system with five levels to inform people about the risk of wildland fires on public lands[1] They convey this rating system using a threat gauge with an arrow pointing to a colored wedge of half of a wheel, with wedges labeled from "Low" to "Extreme" and colored green to red, respectively. This imagery effectively imparts the risk of a forest fire given the current environmental conditions, and evidence suggests that their use of a threat gauge is more likely to reduce dangerous fire behavior than simply using a phrase "Low" to "Extreme" or using some numerical equivalent. Thus, information delivery may be formatted to maximize reception and nudge workers toward greater compliance (22). Here, we examine the use of numbers (percentages), linguistic phrases (e.g., "Low Infection Risk"), and graphical imagery to pass information about the risk that the participant's behavior could result in their animals becoming infected with a disease. Because humans frequently use mental shortcuts, or heuristics, to calculate costs associated with risks, the way the message about infection risk is delivered impacts their decisions (25, 26). By design these shortcuts are quick and are largely based on experience, but they have the capacity to misinform because they perform poorly when experience is lacking, rely on affect or feelings, and do not rely on the heavy use of analytical reasoning (27).

Finally, economic factors and experience with disease likely play critical roles in biosecurity implementation decisions. Biosecurity adoption or compliance may be economically constrained in either direct costs, because biosecurity investments can be quite costly, or in indirect costs, such

[1]https://www.nps.gov/articles/understanding-fire-danger.htm

as opportunity costs, where time pressure has been cited as a major factor leading to lapses in biosecurity practices (28). Evidence suggests that recent experience with a disease outbreak will temporarily increase biosecurity practices (29), although increased biosecurity effort is not ubiquitous (30).

Understanding of decision-making processes has long been gained using economic experiments in controlled environments. Because these experiments are used to gather data, and frequently are couched with the idea of optimizing payouts, they broadly may be defined as serious games—games designed not for enjoyment but rather to gather data or for non-entertainment purposes such as education. While not always labeled as serious games, experimental economic games were pioneered in the work of Nobel Laureate Vernon L. Smith (31, 32) and multiple price list experiments (33, 34). More recently, experiments run on computers and as video games have become increasingly popular across disciplines, including adolescent risk behaviors (35), cognitive ability enhancement (36), and conflict resolution (37). The highly controlled environment within a computer game allows for testing of behavioral differences between, for example, genders (38) and among populations (39) or how individuals behave with increased informational awareness (21). Carefully constructed games provide insight into players' strategic, tactical, and mechanical decisions (40). Importantly, results from experimental computer games have been shown to mirror those from more traditional research instruments such as surveys [e.g., (35)] and, in some cases, games bring about better learning and retention than more traditional teaching methods [e.g., face-to-face, classroom settings or lectures; (41)]. Moreover, serious games offer the possibility of performance-based incentives. Performance-based incentives are used to make experiments more salient and increase effort in the decision making process, over more traditional information gathering techniques, such as surveys (42). As with many other serious game experiments (33, 35, 39), one of the primary sources of study participants was the university community.

Here we developed serious games to simulate a conflict where participants were confronted with a decision about avoidance or compliance with a common biosecurity practice: a "line of separation" at which workers shower and change clothing before entering or exiting areas with livestock. This line of separation is considered highly effective for reducing the risk of disease infection (7, 43). Use of a shower facility, however, carries opportunity costs associated with the time needed for its use, which can result in workers electing to bypass or only partially implement the practice.

We used various experimental scenarios to test participants' willingness to comply with the line of separation shower facility and incur associated opportunity costs in order to avoid potential direct costs associated with infected animals. Treatments varied the following factors: (1) the risk of acquiring an infection in their animals; (2) the certainty/uncertainty of the risk of infection by noting that the infection risk information provided as either a known value or a value that was uncertain; and (3) how the infection risk message was delivered, either with a linguistic phrase (Linguistic), a graphical threat gauge style image (Graphical) or a numerical (Numerical) value. We hypothesized (H1) that participants would become more compliant, and avoid risk as the infection risk increased (33, 44). Additionally, with increased uncertainty associated with the infection risk information, we hypothesized (H2) that we would see more compliance. Finally, we hypothesized (H3) that we would observe the highest compliance rates with infection risk information delivered using a graphical method, then using a linguistic phrase and finally the lowest compliance with infection risk messages delivered using a numeric value.

In addition to the three primary drivers noted above, we looked for secondary behavioral drivers. We posited that participants may immediately react to the economic consequences that result from their animals becoming infected by becoming more prone to comply with the shower facility biosecurity practice, but the tendency toward compliance may diminish with increasing time since the event (44–46). This effect is sometimes referred to as psychological distancing, hyperbolic discounting, or temporal discounting; here we refer to it as a psychological distance effect. We hypothesize (H4) that compliance would decrease with increased time since experiencing an infection.

METHODS

During early phases of this project, research team members met with biosecurity leaders to better understand how farm managers and farm workers make tactical and operational biosecurity decisions and discussed the biosecurity challenges faced by the industry. One outcome of these meetings was an increased awareness that compliance with biosecurity protocols was a serious problem. To study how decisions were made in the domain of biosecurity compliance, we developed two serious games that helped us capture the operational compliance dimensions of livestock biosecurity systems.

Recruitment

We conducted two experiments using serious games to examine behavioral responses to variations in risk messaging. Experiment One was performed entirely at facilities on the University of Vermont campus. Experiment One participants were recruited using Craigslist, University listservs, direct emails, posters, and word of mouth. Approximately, 45% of recruits in Experiment Two were recruited as in Experiment One and through on-campus workshops, and ∼55% were recruited through the online workplace Amazon Mechanical Turks (47). The research team recruited participants from the general public that were at least 18 years old. Because much of the participation was on the University of Vermont campus, many participants were graduate or undergraduate students (see limitations section Limitations). Recruits were told that they would be paid based on their performance during the experiment. Prior to beginning the experiments, participants were shown an informational slideshow that explained the purpose of the study. They were then shown a demonstration of the serious game, which was followed by a screen that gave them the choice to either proceed to game play, or exit and not participate. Institutional Review Board protocols

FIGURE 1 | Screen view of a game round showing infection risk and uncertainty information, the worker and coins (internal tasks) inside the barn, the shower facility (blue arrow) and the emergency exit (red arrow), and the paths taken to attend to outside tasks. During each round, participants collect coins within the barn, then receive a cue to complete an outside task. The participant would then make a decision to use the shower facility or the emergency exit to complete the outside task based on the information provided. After completing the outside task (by touching the outside task space), the participant would return to the barn and collect more coins before the end of the working day.

were followed for an experiment using human participants (University of Vermont IRB # CHRBSS-15-319-IRB).

Experimental Design and Development

The serious game platform used to run both experiments was developed using Unity software (**Figure 1**) (Unity Technologies, Version 5.3.5f1). Participants acted as workers in a simulated swine production facility and were confronted with experimental treatments that differed by the risk of infection if they broke protocol and exited through the emergency exit, and the information presented to them about the infection risk. Each round of the serious game represented one work day from 9 am to 5 pm. Both experiments included 24 rounds of play in addition to one practice round before the start of incentivized play.

The virtual farm worker was controlled by the participant using the arrow keys on a computer keyboard. Each round began with the virtual worker inside the barn, with tasks inside the barn represented as spinning coins; when the worker was moved to a coin the participant earned one experimental dollar. Spinning coins appeared at a rate of one coin every 2 s. One time during each round a high-value outside task would appear: either a feed jam in the silo, a break in the water pipe, or the arrival of a delivery truck. Attending to these outside tasks earned the participant experimental dollars, depending on how quickly they accomplished them. Each of these external tasks started out with a $30 value that decayed by $1 each second. To earn experimental dollars from these high-value tasks, the player needed to leave the barn, and this involved the primary decision in the game: whether or not to use the "shower in—shower out" biosecurity practice.

To use the shower biosecurity practice, the virtual farm worker would enter the shower facility, activating a 5 s counter that simulated showering and changing clothes. Then the participant could exit the facility to attend to the task. The procedure would repeat upon their return to the barn; shower again (which took another 5 s), and then re-enter the facility. The decision to not comply with the biosecurity practice involved leaving through an emergency exit, which had no delay and no opportunity cost, but risked infection. The opportunity cost associated with complying with the shower process was estimated at $7.50 because of the time lost getting to the outside task and the loss of internal task coins during the return to the facility.

In both experiments, if participants chose to use the emergency exit instead of the shower in—shower out facility, they would reduce potential opportunity costs but risk direct losses because their animals could become infected. Infections resulted from a random draw, with the actual risk of infection quantified using the expected risk of infection information presented to the participant. With an infection, the participant's animals would "die," the round would immediately end, and they would lose $50 experimental dollars and any accrued earnings from that round. If their pigs did not get infected, they continued play until the end of the workday.

When the round ended, the number of experimental dollars earned was displayed on the participant's screen. After completing 24 experimental rounds, participants answered a few survey questions, and then were shown a completion code and the amount of real money they had earned. In Experiment One, the conversion rate between experimental and

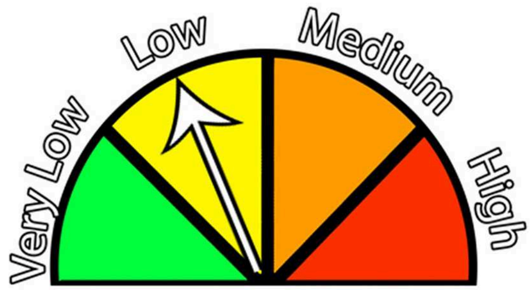

FIGURE 2 | A threat gauge message format was used in Experiment Two's graphical message delivery treatments.

TABLE 1 | Experiment one treatments.

Treatment	*N*
Infection Risk: 5% (Low)	944 (8 rounds*118 participants)
Infection Risk: 15% (Medium)	944 (8 rounds*118 participants)
Infection Risk: 25% (High)	944 (8 rounds*118 participants)
Uncertainty Treatment: Diagnosis Certainty: "100% Certain"	1,416 (12 rounds *118 participants)
Uncertainty Treatment: Diagnosis Uncertainty: "70% Certain"	1,416 (12 rounds *118 participants)
Message Delivery Method: Numeric: "1%," "15%," or "25%"	1,416 (12 rounds *118 participants)
Message Delivery Method: Linguistic: "Low," "Medium," or "High"	1,416 (12 rounds*118 participants)

TABLE 2 | Experiment two treatments.

Treatment	*N*
Infection Risk: 1% (Very Low)	1,068 (6 rounds*178 participants)
Infection Risk: 5% (Low)	1,068 (6 rounds*178 participants)
Infection Risk: 15% (Medium)	1,068 (6 rounds*178 participants)
Infection Risk: 25% (High)	1,068 (6 rounds*178 participants)
Uncertainty Treatment: Contagion Certainty (Single best estimate)	2,124 (12 rounds *177 participants)
Uncertainty Treatment: Contagion Uncertainty (Best estimate plus a range of potential values)	2,124 (12 rounds*177 participants)
Message Delivery Method: Numeric: "1%," "5%," "15%," or "25%"	2,124 (12 rounds*177 participants)
Message Delivery Method: Linguistic: "Very Low," "Low," "Medium," or "High"	2,124 (12 rounds*177 participants)
Message Delivery Method: Graphical: (A threat gauge with arrows used to indicate risk)	2,124 (12 rounds*177 participants)

real dollars was $35 experimental dollars to $1 U.S. Participants then showed their screen to one of the researchers and were paid. In Experiment Two, the conversion rate was either $35 experimental dollars to $1 U.S. for all in-person mediated games or $350 experimental dollars to $1 U.S. plus a base pay of $3.00 for Amazon Mechanical Turk Participants.

Treatments and Variables

Early discussions with industry stakeholders highlighted that biosecurity was not simply a product of infrastructure and protocols, rather it was a product of infrastructure, protocols, and human behavior associated with willingness to use and comply with biosecurity protocols. Treatments were designed to test factors shown to influence willingness to comply, such as risk of loss, information uncertainty, and the media type used to deliver the message. In serious game play, participants received information estimating the infection risk and the uncertainty of that infection risk at the start of each round (**Figure 2**; **Tables 1, 2**). The infection risk information is used by the participant to either accept the risk by using the emergency exit, or accept the opportunity costs associated with the decision to use the shower exit. The infection risk message was delivered numerically (e.g., "5%" infection risk), linguistically (e.g., "low" infection risk), or graphically (i.e., using a threat gauge, Experiment Two only).

In Experiment One, participants received the Uncertainty Treatment in the form of a message describing the confidence in the diagnosis of the infection risk: A farm worker stating his level of certainty as either: "I have been working here for 30 years. I am 100% certain that there is an infection …" or "I just started working here. I am 70% certain that there is an infection …" While playing the round, the participant could see information about the Uncertainty Treatment by looking at a message displayed in the bottom right corner of the screen reporting "Information Certainty: 70%" or "Information Certainty: 100%" (**Figure 1**). Hereafter, this type of Uncertainty Treatment is referred to as Diagnosis Uncertainty.

In Experiment Two, participants received the Uncertainty Treatment using either a fixed level of infection risk or a variable level of infection risk. The message the participant received noted that the uncertainty was based on the understanding of the disease threat: "There is a well-known disease in your system with known contagion rates. There is a "low" probability of your animals getting sick if you leave through the emergency exit." The following information was provided prior to starting each round "There is a poorly understood disease in your system. The best estimate is that there is a "low" probability (the probability could range from "very low to medium") of your animals getting sick if you leave through the emergency exit." As they were playing the round, participants could check the information about the Uncertainty Treatment through a display on the bottom right information box on the game play screen (**Figure 1**). Hereafter, this type of Uncertainty Treatment is referred to as Contagion Uncertainty.

Uncertainty Treatment messages were displayed either numerically (e.g., "1–15%"), linguistically (e.g., "low to high") or graphically using a threat gauge (**Figure 2**, Experiment Two only).

In summary, after an initial examination of results from Experiment One, we noted that there was not a treatment that prompted a strong non-compliance signal (using the emergency exit a strong majority of the time), and thus, we decided to extend the treatment range in Experiment Two by adding an additional "Very Low" or 1% infection risk category. Additionally, discussions with stakeholders and others suggested the use of a graphical image to provide information was effective means of information delivery, and thus we added a graphical, threat gauge-style message delivery method. Thus, Experiment Two had four infection risk treatments that varied from very low (1%) to very high (25%) and three types of infection risk message delivery (Numeric, Linguistic, and Graphical). Both experiments had two Uncertainty Treatment categories related to the infection risk information (Uncertain and Certain).

Three additional variables were used in these experiments. First, because there were numerous rounds, we sought to control for within-experiment learning or behavioral trends (48, 49), and thus used a learning variable, referred to as Play Order, to account for within-experiment changes, such as tendencies to increase biosecurity as the experiment proceeded. Second, we used psychological distance to look for behavioral changes after participant's facilities became infected. Third, in Experiment Two, we used two different participant audience types. One audience group performed the experiment with a moderator present (from the Social Ecological Gaming and Simulation Laboratory, University of Vermont). The other group performed in the Amazon Mechanical Turks online environment (47). Moderated participants received a higher cash payout than those using the Amazon Mechanical Turk platform. These differences may have resulted in differences in salience between groups, and thus, an Audience covariate was included in the analyses.

Analysis

A set of candidate models was developed to explain the decision response by the participants. All candidate models were mixed-effect logistic regressions models compiled using R statistical software (50, 51). Candidate models included treatment variables (**Tables 1**, **2**), i.e., Infection Risk Treatments, Uncertainty Treatments, and Message Delivery Treatments, and interaction terms between treatments as well as the predictor variables: (1) psychological distance, (2) the learning variable: play order, and (3) in Experiment Two only Audience type. Participant was considered a random effect. Parameter estimation from mixed-effect binary logistic regressions are presented as logit coefficients that can be used to predict the probability (from 0 to 1) of a binary response, in this case, the probability that the participant would use the shower biosecurity facility given the combination of treatment information provided in the particular scenario. Logit coefficients can be exponentiated to generate odds ratios, which provide a measure of the odds that an individual will choose to use the shower biosecurity facility instead of the emergency exit. With odds ratios, a 1:1 ratio, presented as the value 1, indicates that there are even odds for the choice, and thus, if 1 is included in the odds ratio confidence interval, it may be equally possible that the participant will choose either the shower or the emergence exit and indicates that the variable does not have a significant signal.

One method to find the most parsimonious model when the number of possible combinations of explanatory variables is large is to create a set of plausible candidate models, and test to see how well each of them explains the data. We used an information-theoretic approach for candidate model selection (52, 53). Candidate model selection methodology and results are presented in **Supplemental Material Appendix A**.

RESULTS

Experiment One

Data were collected from 118 participants in Experiment One. Fifty-four identified as female, 59 identified as male, and 5 choose not to identify with a gender. The mean age of the participants was approximately 25.4 years old. Payouts for this

TABLE 3 | Results of the selected best fit, mixed-effect logistic regression model (Model 8; see **Table S1**) for Experiment One.

Parameter	Odds Ratio	Lower Bound	Upper bound	*p*-values
Intercept (Infection Risk @ 5%, Linguistic Message, Diagnosis Certainty @ 70)	3.337	1.811	6.149	**<0.001**
Diagnosis Certainty @ 100	0.206	0.132	0.321	**<0.001**
Psychological Distance	0.516	0.345	0.774	**0.001**
Numeric Message	0.448	0.291	0.690	**<0.001**
Infection Risk @ 15%	4.342	2.662	7.083	**<0.001**
Infection Risk @ 25%	5.223	3.168	8.612	**<0.001**
Order of Play	1.009	0.994	1.025	0.231
Diagnosis Certainty @ 100 by Numeric Message	1.451	0.775	2.716	0.245
Numeric Message by Infection Risk @ 15%	0.565	0.294	1.084	0.086
Numeric Message by Infection Risk @ 25%	0.868	0.446	1.692	0.678
Diagnosis Certainty @ 100 by Infection Risk @ 15%	8.152	3.937	16.883	**<0.001**
Diagnosis Certainty @ 100 by Infection Risk @ 25%	25.046	10.259	61.143	**<0.001**
Diagnosis Certainty @ 100 by Numeric Message by Infection Risk @ 15%	0.332	0.128	0.861	**0.023**
Diagnosis Certainty @ 100 by Numeric Message by Infection Risk @ 25%	0.451	0.147	1.389	0.166

Depicted here are the odds ratios for the fixed effects describing relationships with the binary response variable: compliance with the biosecurity protocol. Bold values indicate significance at alpha = 0.05.

experiment averaged approximately $28 with a $19 minimum and a $37 maximum.

The AIC-selected best candidate model included Participant as a random effect and the fixed effects Infection Risk, Diagnosis Certainty, Message Delivery Method Psychological Distance and Play Order, as well as all interaction terms between Infection Risk, Diagnosis Certainty and Message Delivery Method (**Supplemental Material Appendix A**).

Logistic regression results presented in both experiments quantify the probability that a participant will comply with the shower biosecurity practice instead of using the emergency exit. Results presented in **Table 3** are odds ratios. The top line represents the baseline odds ratio associated with the treatment combination of 5% Infection Risk, message delivered using a Linguistic phrase and with the Uncertainty Treatment set at 70% diagnosis certainty. The 3.337 odds ratio presented on the first line in **Table 3** (intercept results) should be interpreted as participants are 3.337 times as likely to use the shower facility instead of using the emergency exit. The rest of **Table 3** (i.e., excluding the top data line) are odds ratios compared with the baseline, intercept ratio. Odds ratio values in the table should be interpreted relative to the baseline treatment combination, i.e., the intercept value. For example, participants that received the infection risk information with a numeric message instead of the intercept value (Linguistic) had an odds ratio of 0.448, meaning they were 0.448 times more likely to use the shower door *than* the emergency door (or inversely 2.23 times more likely to use the emergency exit) than if they received information about the infection risk using a Linguistic phrase. If the odds ratio confidence interval includes 1 then it is unclear if or how the predictor variable will affect their decision to comply with the shower practice, and thus, variables that do not have 1 included in their confidence interval are significant variables. Odds ratios <1 indicate that it is relatively more likely that the participant will choose to exit through the emergency exit, whereas values above 1 indicate that they are more likely to comply with the suggested biosecurity practice by using the shower in—shower out door.

We found significant main effects, two-way interactions and a three-way interaction between Message Delivery Method, Infection Risk and Diagnosis Certainty (**Figures 3**, **4**, **Table 3**).

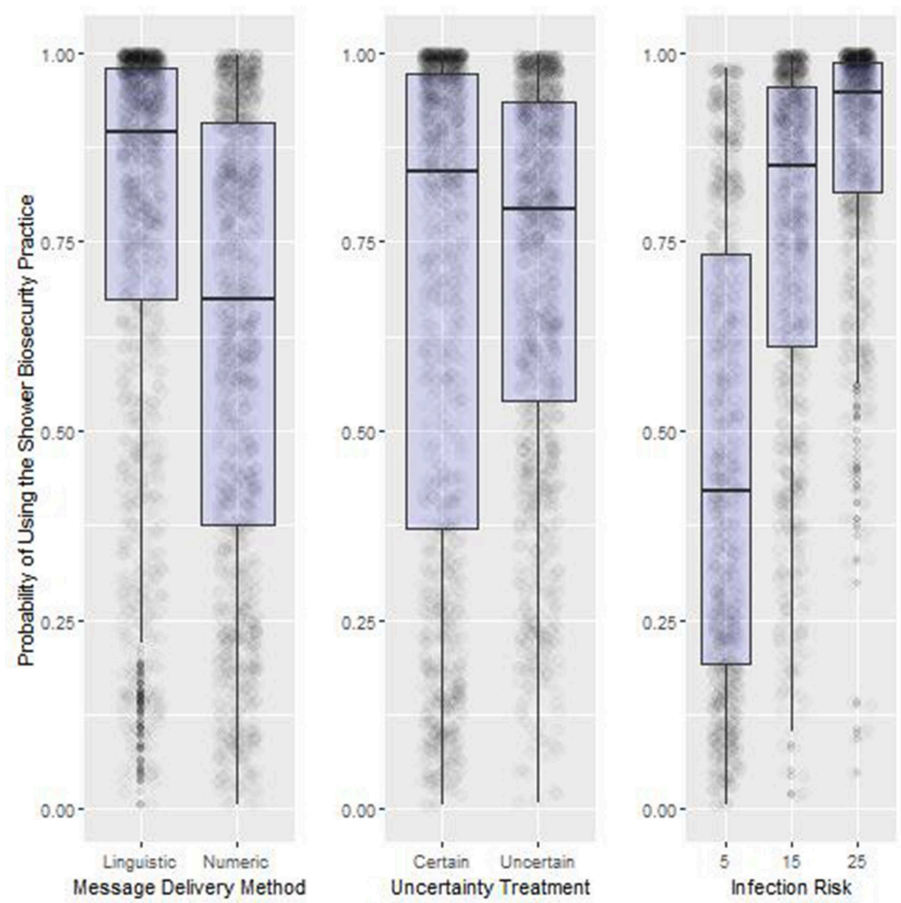

FIGURE 3 | Summary results of the main treatment effects from Experiment One. Box-plot of the probability of using the shower biosecurity practice by the main effects, Message Delivery Method, Uncertainty Treatment, and Infection Risk, Lower, and upper box boundaries 25 and 75th percentiles, respectively, line inside box median, overlaid on model predicted data values.

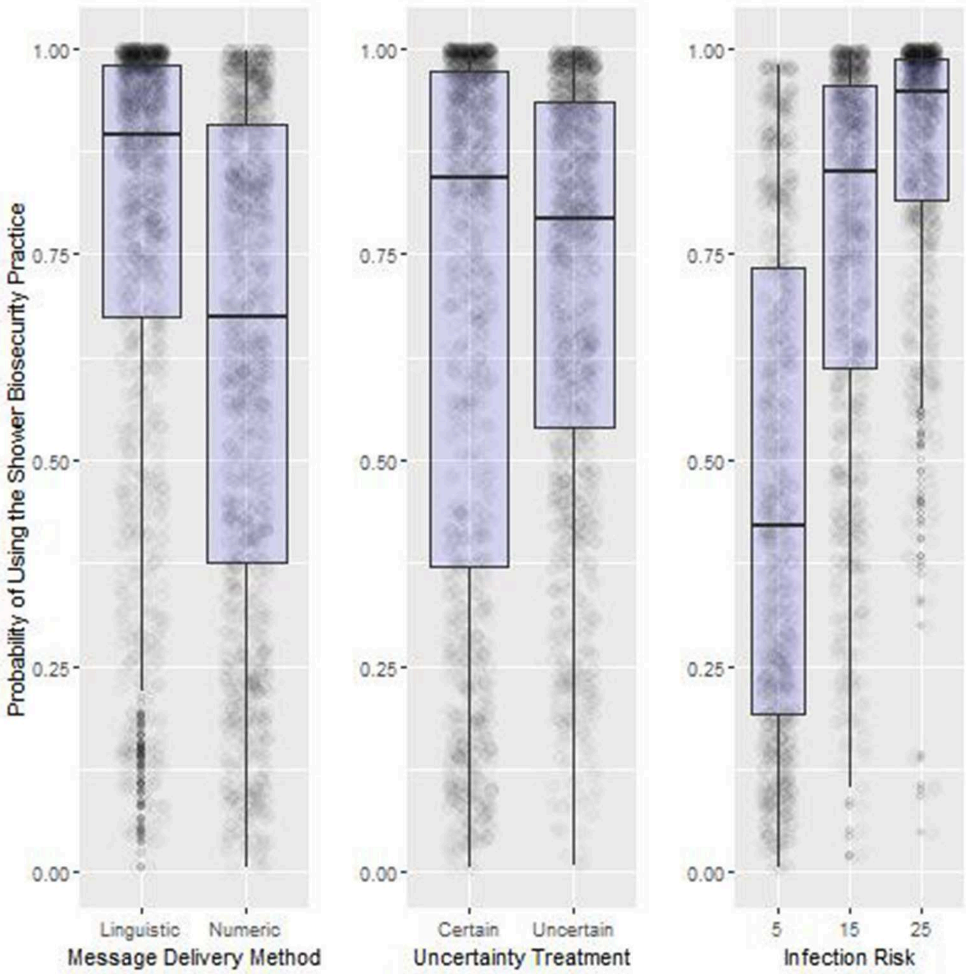

FIGURE 4 | Summary results of the interaction effects between treatments from Experiment One. Box-plot of the probability of using the shower biosecurity practice by the interaction effects between Message Delivery Method, Uncertainty Treatment, and Infection Risk, Lower and upper box boundaries 25 and 75th percentiles, respectively, line inside box median, overlaid on model predicted data values.

Main Effects (H1–H3)

Odds of compliance with the shower in-shower out biosecurity practice increased significantly as infection risk increased from 5% (46.4% compliance) to 15% (75.7% compliance) to 25% (93% compliance) (**Figure 3** Right Panel). Shower use was much higher when the risk message was a linguistic phrase (77.7%) vs. numeric probability (62.3%) (**Figure 3** Left Panel). Changing the Uncertainty Treatment from an message received from an advisor that was 70% certain of their report compared to 100% certain of their report resulted in a relatively small overall increase in the probability of observing participants using the shower biosecurity practice (Uncertainty: 71.6%. Certainty: 68.3%. **Figure 3** Center Panel).

Interaction Effects (H1–H3)

Significant interactions with infection risk and message delivery type were observed (**Tables 3**, **4**, **Figure 4**). The probability that participants would comply with the shower biosecurity depended upon the combination of treatments in the simulation with compliance values ranging from 31.2% with the treatment combination of 5% risk, message delivered numerically, and with 100% diagnosis certainty, to very high overall compliance when the message was delivered with certainty using a linguistic phrase (98.1%).

Experiment Two

Of the 178 participants in Experiment Two, 76 were recruited as in Experiment One and through on-campus workshops, and 102 were recruited through Amazon Mechanical Turks. Ninety-nine identified as male, 76 identified as female, and three chose not to identify with a gender. The mean age of participants in Experiment Two was approximately 30.3 years old. Payouts for university community participants in Experiment Two averaged approximately $27 with a $16 minimum and a $35 maximum. Amazon Mechanical Turk participants received a base pay of $3.00 with additional performance bonuses

TABLE 4 | Experiment One interaction affects.

Infection risk (%)	Uncertainty treatment	Message delivery	Frequency of compliance (%)
5	Certain	Linguistic	38.6
5	Certain	Numeric	31.2
5	Uncertain	Linguistic	65.8
5	Uncertain	Numeric	50.0
15	Certain	Linguistic	91.2
15	Certain	Numeric	61.4
15	Uncertain	Linguistic	84.9
15	Uncertain	Numeric	65.4
25	Certain	Linguistic	98.1
25	Certain	Numeric	89.5
25	Uncertain	Linguistic	87.5
25	Uncertain	Numeric	76.3

Observed frequency of use of the shower in–shower out biosecurity practice.

ranging averaging \$2.98, ranging from a minimum of \$1.28 to a maximum of \$3.84.

The AIC-selected best candidate model for Experiment Two included Participant as a random effect and the fixed effects Infection Risk, Diagnosis Certainty, Message Delivery Method, Psychological Distance and Audience, as well as the two-way interaction terms between Infection Risk and Message Delivery Method, and between Infection Risk and Contagion Certainty. Model selection results and details can be found in **Supplemental Material Appendix A**.

Main Effects (H1–H3)

As in Experiment One, odds ratios observed in Experiment Two confirmed the hypotheses about the main treatment effects (**Table 5**, **Figure 5**). Note that an odds ratio with a 95% confidence interval excluding the value 1 is considered significant with values <1 suggesting the odds of observing the shower behavior are less than the intercept, while treatments with odds ratio values above 1 are more likely to trigger compliance behavior. Inference from the selected best candidate model suggests that the use of the shower increased significantly as infection risk increased from 1% (23% compliance) to 5% (59% compliance) to 15% (85% compliance) and finally to 25% (93% compliance; **Figure 5**, Right Panel). Contagion Uncertainty, i.e., being unsure of the risk of acquiring an infectious disease with the use of the emergency exit, resulted in greater compliance with the shower biosecurity practice (Contagion Uncertainty: 69% compliance. Contagion Certainty: 62% compliance. **Figure 5**, Center Panel). Use of a Graphic (i.e., a threat gauge) to deliver the infection risk information message increased shower use over both the Linguistic and Numeric messages (Graphical delivery: 72% compliance; Linguistic delivery 69% compliance; Numeric delivery 60% compliance. **Figure 5**, Left Panel).

Interaction Affects (H1–H3)

Substantial variation can be explained by the main effects, especially the infection risk treatment. Yet, the effects of these effects become more pronounced when we control for other variables in the system (**Tables 5**, **6**, **Figure 6**). Compliance ranged from 16.7% with the treatment combination of 1% Infection Risk, message delivered numerically and with certainty, to the most frequent compliance at 98.1% when the Infection Risk was 25%, messages were delivered graphically and with uncertainty.

Psychological Distance (H4)

In both experiments, evidence (odds ratios of 0.516 and 0.574 in Experiments One and Two, respectively), suggests that individuals are modifying their behavior based on the psychological distance by increasing the probability that they will comply with the biosecurity practice after becoming infected (**Tables 3**, **5**). This was quantified by the number of rounds since they last experienced the economic consequences that results from their animal becoming infected.

Learning Effect and Audience

In Experiment 1, the Play Order (learning) variable was selected for inclusion in the AIC-selected best candidate model, but it did not have support as a significant variable in the model. This indicates that it explained some of the variability in the data but did not have a consistent effect. Order of play was not selected as an important variable in Experiment Two.

A small difference in behavior was detected between the different participant types with Amazon Mechanical Turk participants taking more risks than participants at in experiment moderated by personnel from the Social Ecological Gaming and Simulation Laboratory (Amazon Mechanical Turks, 62% compliance. Moderated 69% compliance).

DISCUSSION

Common risks faced in agriculture often relate to the safety of the execution of tasks or the applications of products or technology. Farmers make decisions regularly on how to manage their farms, plants and animals and their risk perception influences their decisions (18). Risk messages are common and they aim at increasing awareness and/or understanding about the level of risk and motivating a behavioral change that reduces it.

The degree to which the risk information is received, its value and usefulness is affected by many factors including how it is framed and presented, and the recipient's situation/context at the delivery (54–58). In particular, the probabilistic dimension of risk is challenging to grasp for the general public. One line of research, inspired by risk communication theories, shows that the type of message chosen to convey probabilistic information (for example numeric, linguistic, graphical, or visual) has an effect on the degree to which perceived risk will change behavior (55, 56, 59). Overall, there is no one specific suggestion on which message format is best (55). The numeric format is precise and suggests scientific rigor but it

TABLE 5 | Results of the selected best fit, mixed-effect logistic regression model (Model 2; see **Table S2**) for Experiment Two.

Parameter	Odds ratio	Lower bound	Upper bound	*P*-value
Intercept (Contagion Certainty, Infection Probability @ 1%, and Graphical Message)	0.267	0.119	0.596	**0.001**
Contagion Uncertainty	1.173	0.795	1.732	0.421
Psychological Distance	0.574	0.339	0.970	**0.038**
Audience: SEGS Moderated	4.509	2.110	9.638	**<0.001**
Linguistic Message	0.365	0.208	0.639	**<0.001**
Numeric Message	0.270	0.156	0.468	**<0.001**
Infection Probability @ 5%	12.086	6.269	23.301	**<0.001**
Infection Probability @ 15%	352.507	144.614	859.261	**<0.001**
Infection Probability @ 25%	1571.303	438.113	5635.517	**<0.001**
Contagion Uncertainty by Infection Probability @ 5%	4.922	2.914	8.314	**<0.001**
Contagion Uncertainty by Infection Probability @ 15%	1.170	0.658	2.079	0.594
Contagion Uncertainty by Infection Probability @ 25%	1.010	0.500	2.040	0.977
Linguistic Message by Infection Probability @ 5%	1.040	0.493	2.193	0.918
Numeric message by Infection Probability @ 5%	0.399	0.196	0.816	**0.012**
Linguistic Message by Infection Probability @ 15%	0.934	0.355	2.463	0.891
Numeric message by Infection Probability @ 15%	0.196	0.079	0.489	**<0.001**
Linguistic Message by Infection Probability @ 25%	1.439	0.343	6.035	0.619
Numeric message by Infection Probability @ 25%	0.176	0.049	0.632	**0.008**

Depicted here are the odds ratios for the fixed effects describing relationships with the binary response variable: compliance with the biosecurity protocol. Bold values indicate significance at alpha = 0.05.

may not connect with gut-level reactions in people who do not have familiarity with methematical concepts (low numeracy). The verbal format allows more fluid communication but it might lack precision. Graphical and visual formats have become common in conjunction with numeric or verbal risk messages because they can encapsulate data, patterns, and matematical relationships. The immediacy of graphical formats is very appealing but it needs the right skills and/or information for interpretation. Recomendations on how to improve messages of risk probability are suggested in the paper reviews by Lipkus (55) and Visschers et al. (56). Most reviews published on risk-probability communication are in the medical field. The need for guidance and research on effectively using risk messages in any form (visual, graphic, linguistic or numerical) is growing. There are still important questions about how to compose messages for best efficacy in the farming context. With our experiment, we aimed at understanding the effect of message type at the operational level of biosecurity in the hog farming system. In a recent publication, Merrill et al. (21) showed that the type of information provided to inform about disease risk in a hog production system affects the direction of behavioral change. Specifically, information on disease presence lead to increased investment in biosecurity. On the other hand, information about neighbors' biosecurity level triggered a free rider effect in a significant fraction of individuals. Our current study is therefore timely and essential to test and tailor risk messages in the specific context of biosecurity compliance in livestock production systems.

We examined effects of different aspects of infection risk information and delivery on compliance with biosecurity by testing for effects of disease infection risk, information uncertainty, and message delivery methods. As hypothesized, compliance with the biosecurity practice of using the shower facility increased significantly with increasing disease infection risk. With increased diagnosis and contagion uncertainty, participants increased the frequency of their safe choices (compliance with biosecurity). Graphical information in the form of a threat gauge increased compliance more than information delivered linguistically, with the least use of the shower facility associated with infection risk information delivered numerically. We also found evidence of psychological distancing—the more time that passed since participants experienced the consequences of their animals getting a disease, the less compliant they became.

Limitations

Social, psychological and behavioral economics studies frequently use participants from a portion of society, such as a student population, and attempt to extrapolate to a larger or more diverse group. This could lead to bias if the participants behave differently than the population of interest. Participants in the present study were not recruited based on experience working in swine production facilities and thus, participant behavior may not accurately reflect worker behavior. For example, U.S. farmers are thought to be relatively more risk seeking than the general public (18). However, Zia et al. (60), using a similar serious game methodology to study risk and information in the swine industry, did not find a significant difference between swine industry stakeholders and behavior of those not known to

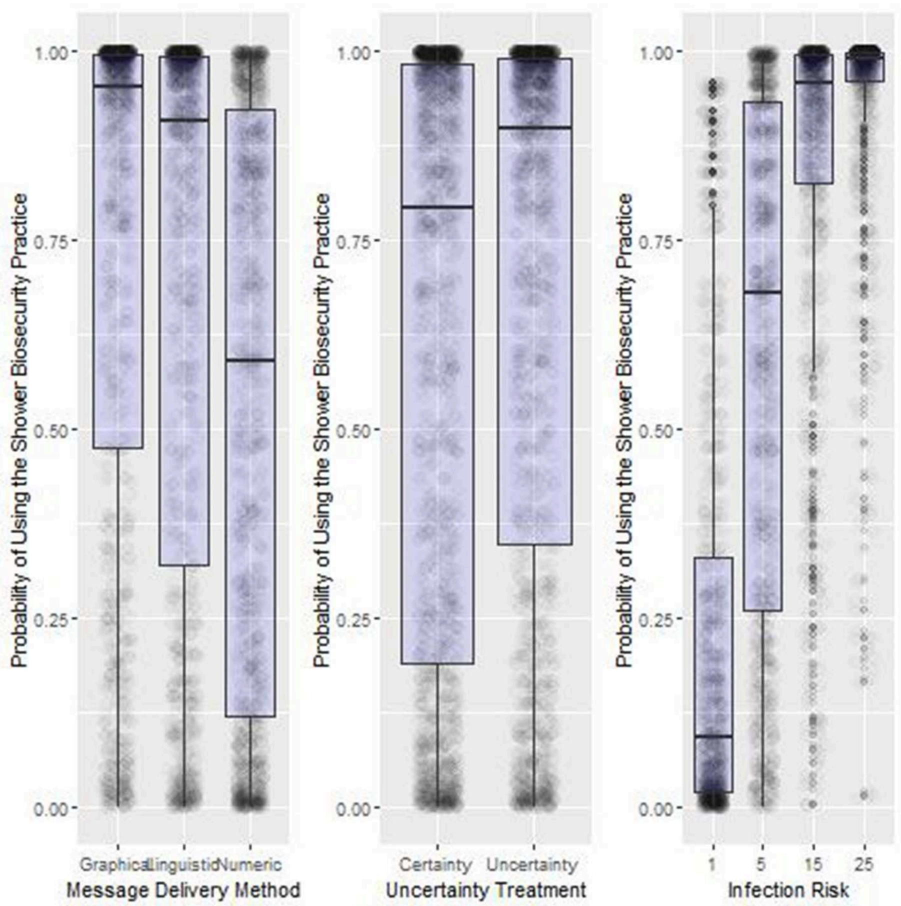

FIGURE 5 | Summary results of the main treatment effects from Experiment Two. Box-plot of the probability of using the shower biosecurity practice by the main effects, Message Delivery Method, Uncertainty Treatment, and Infection Risk, Lower and upper box boundaries 25 and 75th percentiles, respectively, line inside box median, overlaid on model predicted data values.

have any experience in the industry. Their conclusions should be taken with some caution because their sample population of ∼100 participants may not have been large enough to detect a difference in the behavior between populations. People are complex and make decisions based on a number of rational and irrational factors. Because of this complexity, true differences in the decision process between population groups may be hard to tease out. Moreover, experience will alter one's heuristics but may not do so consistently. Therefore, workers in the swine production industry may behave differently than participants selected for our study, yet because workers are complex and each have their own set of objectives, any bias that exists may not be consistent. In addition, we attempted to reduce the potential for participant subset bias by using multiple, distinct participant group types (i.e., Amazon Mechanical Turk participants and the community recruited to participate on the University of Vermont campus). Using multiple groups allowed us to control for statistical differences among participant groups and should reduce bias that may be associated with a particular subset e.g., bias that could be generated if participants were from only a student population. Although, data from an all-worker participant population would be ideal, it is logistically impractical and good evidence exists (60) that behavioral differences between participant populations may be minimal.

Infection Risk (H1)

The experiments were designed with PEDv in mind. The number of hog facilities in the U.S. was estimated at 69,100 in 2011[2]. At the height of the PEDv outbreak in 2014, the number of infected facilities reached over 1,200 (61), putting the probability of infection at approximately 1.75%. This value is close to the "very low" treatment in the present study, but when considered as a series of choices over the course of a week, reflects that the likelihood of an infection break per behavioral choice is exceptionally low. However, in aggregate, many choices can impact biosecurity and aggregate decisions may approximate the 1% treatment in Experiment Two. Moreover, for any given region during an outbreak, the probability may approach much higher

[2]https://www.porkbusiness.com/article/usda-estimates-number-us-swine-operations-farms

TABLE 6 | Experiment Two interaction affects.

Infection risk	Uncertainty treatment	Message delivery	Frequency of compliance (%)
1	Certainty	Graphical	28.4
1	Certainty	Linguistic	21.9
1	Certainty	Numeric	16.7
1	Uncertainty	Graphical	30.4
1	Uncertainty	Linguistic	23.1
1	Uncertainty	Numeric	17.8
5	Certainty	Graphical	59.6
5	Certainty	Linguistic	53.0
5	Certainty	Numeric	30.0
5	Uncertainty	Graphical	82.0
5	Uncertainty	Linguistic	76.8
5	Uncertainty	Numeric	54.4
15	Certainty	Graphical	94.5
15	Certainty	Linguistic	90.0
15	Certainty	Numeric	66.1
15	Uncertainty	Graphical	95.7
15	Uncertainty	Linguistic	92.0
15	Uncertainty	Numeric	70.6
25	Certainty	Graphical	97.8
25	Certainty	Linguistic	97.3
25	Certainty	Numeric	83.9
25	Uncertainty	Graphical	98.1
25	Uncertainty	Linguistic	97.6
25	Uncertainty	Numeric	85.6

Observed frequency of use of the shower in—shower out biosecurity practice.

numbers, which we reflect using our higher treatment levels of 15 to 25%.

Results of this study may extend for use in communicating to farm workers, nudging behavior toward greater biosecurity compliance, and thus, reducing their facility's risk (8). By design we varied the risk of infection if the participants chose to exit through the emergency exit. In the high risk treatments, we anticipated that most of the individuals would avoid risk by complying with the suggested biosecurity practice and conversely, we hypothesized that most would choose not to comply in the low risk scenarios. As hypothesized, we found significant jumps in compliance as the infection risk increased.

In Experiment One, less than half complied with the low (5%) Infection Risk treatments, around ¾ complied with the medium Infection Risk treatments and compliance approached 90% with the high Infection Risk Treatments. After running Experiment One, we recognized that we should include an additional very low risk category to prompt even more non-compliance behavior. Similar patterns were observed in Experiment Two with less frequent compliance (around a ¼) in the very low, 1% Infection Risk treatments, with an increase in the choice to use the biosecurity practice (over half complied) as the risk of infection increased to low, 5% Infection Risk treatments, about 85% compliance with the medium, 15% Infection Risk Treatments, and compliance over 90% with the high, 25% Infection Risk treatment. The wide range of compliance observed by treatment confirmed that our simulation was able to elicit a substantial range of behaviors, and thus observe how the treatments combined to observe emergent patterns of behavior. These findings are supported by the risk aversion literature (33, 34, 44).

Infection Risk Uncertainty (H2)

Supporting previous research, we found evidence for an uncertainty aversion effect in both experiments (62). Participants were less apt to use the emergency exit to increase their payouts if they believed that the information about the risk associated with the behavior was uncertain. However, this effect was not exceptionally pronounced as a main effect because of the variation associated with infection risk and message delivery format. However, when we examine uncertainty when controlling for other variables, the effect is dramatic. In Experiment One, when infection risk was set at 5%, and message was delivered with certainty as the Linguistic phrase "Low," participants chose to use the shower biosecurity practice 38.6% of the time, and 65.8% when the infection risk message was delivered with uncertainty, which marks over a 70% increase in compliance associated with uncertainty aversion. Similarly, in Experiment Two, with the Infection Risk at 5%, and numerical message delivery, 30.0% complied with biosecurity when infection risk information was certain, whereas 54.4% complied when there was uncertainty about infection risk. So in these two scenarios, by simply changing the level of certainty in the infection risk information, we altered compliance from ∼1/3 probability of using the shower biosecurity to on average around 3/5 probability of compliance. These shifts suggest exceptional uncertainty aversion constrained by situational risk (62, 63). An exception to the uncertainty aversion effect appeared in Experiment One, when significant infection risk prompted a strong majority of participants to use the shower facility. In this case, adding uncertainty slightly reduced the likelihood of using the shower facility. This slight decrease may stem from the wording that could have been interpreted to mean "I believe the infection risk is high, but there is a chance it could be medium or low." With this interpretation, uncertainty in this situation would produce a bias because the direction of uncertainty could only reduce the probability of infection.

Message Delivery Format (H3)

Compliance with biosecurity protocols was observed more frequently when the infection risk was conveyed using a graphical representation (the threat gauge, **Figure 2**), followed by messages delivered using a linguistic phrase, with the least compliance when a numerical representation of the infection risk (**Tables 3**, **5**). The effect of message delivery format becomes more pronounced when the other two treatment variables are controlled. In Experiment One, we observed the most extreme changes in behavior with the Infection Risk at 15%, and with messages delivered with certainty, 91.2% of participants used the shower biosecurity practice when the message was delivered using the linguistic phrase "Medium Risk" contrasted with 61.4% when the risk message was delivered numerically as

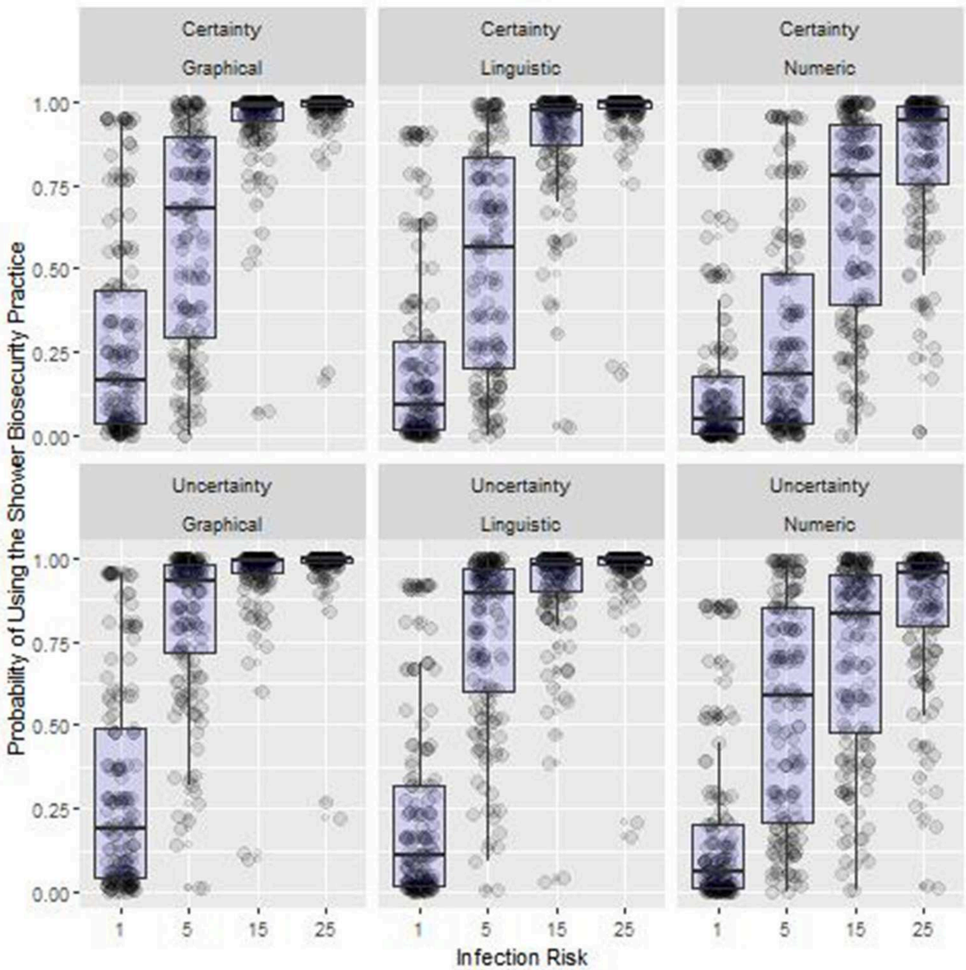

FIGURE 6 | Summary results of the interaction effects between treatments from Experiment Two. Box-plot of the probability of using the shower biosecurity practice by the interaction effects between Message Delivery Method, Uncertainty Treatment, and Infection Risk, Lower and upper box boundaries 25 and 75th percentiles, respectively, line inside box median, overlaid on model predicted data values.

"15%." In Experiment Two, we observed the most dramatic behavioral shift associated with message delivery type with the treatment combination of Infection Risk at 5%, and the message delivered with certainty. With this treatment combination, there was a 59.6% probability that participants would comply when the message was delivered graphically, and a 30.0% compliance rate when the message was delivered numerically. These results corresponds well with previous research that suggests using graphical representations of information for efficient information transfer (42). Moreover, research has noted that people are notoriously poor at calculating cost loss functions using numerical probabilities (24, 44). Because we requested quick decisions for each scenario, we suggest that participants were using mental shortcuts to calculate the if the risk was worth the potential benefit, and in the high risk scenario the numeric risk was 25%. Compared to 100%, this value is relatively low, and experientially, many may have quickly considered the likelihood of an infection to be low without analytically assessing the relative benefit and relative costs of their decision (25, 27). In this case, there was a 75% chance of earning approximately an extra $9 experimental dollars and a 25% chance of losing around $80 experimental dollars. If participants had fully assessed those terms, it is unlikely many would have chosen to use the emergency exit. Moreover, Slovic et al. (25) suggest that the feeling, or affect, behind a decision can sometimes discount probabilities so that the decisions are made without fully analyzing the values but rather simply by assessing whether the decision "feels" risky. Thus, participants may have observed the numeric "15%" or "25%" and intuitively felt that the risk was low, and thus, made a gut decision to exit through the emergency exit. The graphical image, using a threat gauge, may have triggered an additional affect, associated with risk and prompted additional constrain over the simple linguistic phrase. These results reinforce the impact of the method of message delivery, because many of our quick decisions rely on mental shortcuts, based on previous experience (26, 27).

Psychological Distance (H4)

Historic exposure to an infection ties in with the concept that humans use experientially-informed mental shortcuts to help make decisions. The relationship with passage of time and the influence of experience is captured in the concept of psychological distance. In both experiments participants that had just had animals infected because of their choice to use the emergency exit were approximately twice as likely to use the shower facility compared to those that were nearing the end of the experiment and had not experienced an infection. Thus, participants behaved with increasingly risky behavior as time passed since they had experienced an infection. This evidence for psychological distancing (45, 46, 64) has profound education implications for the industry because it reinforces the need for temporally frequent reminders or messages, especially those messages that support internalization of the material, explain the problem and provide appropriate actions (65), as well as assist in reduction of the discounting through reinforcement-learning (66).

Selecting Appropriate Combinations for Effective Messaging

As noted above, the combination of treatments could change behavior from infrequent compliance to nearly ubiquitous compliance. Even without altering the actual Infection Risk, the rate of compliance with the shower in—shower out biosecurity practice could be dramatically shifted with messaging. For example, in Experiment One, with the treatment combination of 5% risk, numerical message delivery, and with 100% diagnosis certainty, we observed that just under a third (31.2%) of the participants complied by using the shower biosecurity practice. Yet almost two-thirds (65.8%) of participants complied when the message was delivered with uncertainty about the diagnosis and with the message delivered using a linguistic phrase. Within the subset of high infection risk treatments from Experiment One, when the message was delivered numerically with uncertainty, compliance was observed in ∼76% of trials, whereas if the infection risk message was delivered using a linguistic phrase with certainty, we observed approximately 98% compliance with the shower biosecurity practice. This evidence suggests that we can influence behavior through explicit message design and delivery with the potential to radically change behavior, with an intended goal of changing the default behavior and the culture within the system (67).

Compliance with existing biosecurity practices is one of the critical issues that confronts managers in the swine industry (8). In August 2018, the authors were requested to run a workshop for industry professionals to help assist in designing messages to improve biosecurity compliance in their production system. In light of this workshop, we recognize that compliance is something that managers struggle with on a daily basis.

> "I would be happy if I could get my guys to use soap."–An industry professional at a workshop titled *Improving Workplace Compliance Through Message Development*. Minnesota, August 2018.

Human behavior in the animal livestock industry remains a challenge because of the serious ramifications of a disease outbreak and the ongoing fight against complacency (8, 15). Here we confirm that compliance with existing biosecurity measures may be influenced by the way that we provide information to those working in the facilities. Graphical messages that make note of the inherent uncertainties rather than numeric "best estimates" of the risk of contagion should provide the most reliable compliance with existing biosecurity rules. If graphical message delivery is not an option, our research provides evidence that the use of linguistic phrases should be encouraged over the use of numerical delivery. Costs for biosecurity failures can be exceptionally high. In addition to the direct costs associated with animal mortality and stunted growth, owner operators and their workers can experience the loss of livelihoods and even experience an array of mental health issues. Awareness that psychological discounting temporally (and likely spatially) will distract workers reinforces the idea that biosecurity communication and trainings need to be frequently reinforced.

CONCLUSION

As we have noted, the types of factors that influence the abilities of farm workers to comply with biosecurity protocols like the shower-in-shower-out facilities simulated in these experiments are complex. Drawing on a number of factors that industry leaders have highlighted for the researchers, three possible influences were tested. The first is when the infection risk is communicated, we see that the higher the risk, the stronger the compliance.

The second influence is the level of certainty that the worker has in the risk that their behavior may lead to an infection. In Experiment One variations in this certainty as a matter of both trust in the experiences of an experienced farmer (who is 100% certain of his forecast) and the less trustworthy experiences of a new, less experienced farmer (who is only 70% certain of his forecast). Operationally, we can interpret this as the relative importance of the medium through which a risk message is conveyed. Our results demonstrate that the assuredness of information about the risk associated with behaviors may reduce the rates of compliance with biosecurity protocols. In Experiment Two, uncertainty was associated with epidemiological factors. Regardless of the type of uncertainty, increased uncertainty led to increased compliance. This result may seem counter-intuitive. However, the selection of infection risks examined were all relatively low from a pure probability perspective—at the maximum, infection risk was 25%. In general, people tend to discount the probability that something bad will happen if its likelihood is low (44). When that probability is more certain, this discount effect is more likely, because when a probability is less certain, the potential for even higher rates of probability are there, leading to increased risk aversion (62, 63, 68).

Thirdly, these findings confirm that the method by which risk is conveyed matters. Graphical displays are more effective than linguistic, followed by numerical displays.

If findings are extended to the farm level, the operational and policy implications from this study are summarized as follows. If routine compliance with biosecurity protocols is desirable, then one can expect significant variance in responses as risk threat is communicated to farm workers. These findings suggest that although risk communication is still likely very important, the active and ongoing reporting of risk threat, regardless of the medium (the assuredness of the messenger) and means of communication are influential and should be considered with the audience preferences in mind.

The findings of this project suggest that messages delivered using graphical means to convey disease infection risk, include infection risk uncertainty, and are delivered with relatively high frequency to reduce the psychological distancing effect, have the potential to dramatically improve biosecurity compliance on livestock facilities. While we acknowledge that idiosyncrasies in human nature will not disappear, we believe that even small improvements in compliance can have a profound impact in the reduction of disease, improving the welfare of animals and the livelihoods of workers across this industry.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the Collaborative Institutional Training Initiative via the Committee on Human Research Behavioral and Social Sciences at the Research Protections Office at the University of Vermont. The protocol was approved by the Committee on Human Research Behavioral and Social Sciences.

AUTHOR CONTRIBUTIONS

SCM, SM, CK, AZ, SW, LT, JS, EC, TS, and DS assisted with design and conceptualization of the experiment and underlying serious game. LT, EC, and SCM helped with data curation. SCM, SM, and GB worked on data analysis. Project funding was generated with the help of JS, SCM, CK, AZ, and TS. Experiments were conducted by SCM, SM, LT, and EC. Software development was primarily led by LT and EC. Initial manuscript drafts were created by SCM and SM. Subsequent manuscript editing and retooling was completed by all authors, SCM, SM, CK AZ, LT, EC, GB, SW, TS, DS, and JS.

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SUPPLEMENTARY MATERIAL

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REFERENCES

1. MacDonald JM, Hoppe RA, Newton D. *Three Decades of Consolidation in U.S. Agriculture*. United States Department of Agriculture, Economic Research Service (2018).
2. Wiltshire SW. Using an agent-based model to evaluate the effect of producer specialization on the epidemiological resilience of livestock production networks. *PloS ONE. (*2018) 13:22. doi: 10.1371/journal.pone.0194013
3. Buhnerkempe MG, Tildesley MJ, Lindstrom T, Grear DA, Portacci K, Miller RS, et al. The impact of movements and animal density on continental scale cattle disease outbreaks in the United States. *Plos ONE. (*2014) 9:10. doi: 10.1371/journal.pone.0091724
4. Dee S, Clement T, Schelkopf A, Nerem J, Knudsen D, Christopher-Hennings J, et al. An evaluation of contaminated complete feed as a vehicle for porcine epidemic diarrhea virus infection of naive pigs following consumption via natural feeding behavior: proof of concept. *BMC Vet Res*. (2014) 10:176. doi: 10.1186/s12917-014-0176-9
5. Pudenz C, Schulz L, Tonsor G. *Biosecurity and Health Management by U.S. Pork Producers - 2017 Survey Summary*. Iowa State University Extension and Outreach (2017).
6. Paarlberg PL. Updated estimated economic welfare impacts of porcine epidemic diarrhea virus (PEDV). In: Working Paper #14–4. Lafayette, IN (2014).
7. Andres VM, Davies RH. Biosecurity measures to control salmonella and other infectious agents in pig farms: a review. *Comprehen Rev Food Sci Food Saf*. (2015) 14:317–35. doi: 10.1111/1541-4337.12137
8. Ritter C, Jansen J, Roche S, Kelton DF, Adams CL, Orsel K, et al. Determinants of farmers' adoption of management-based strategies for infectious disease prevention and control. *J Dairy Sci*. (2017) 100:3329–47. doi: 10.3168/jds.2016-11977
9. Hoe FGH, Ruegg PL. Opinions and practices of Wisconsin dairy producers about biosecurity and animal well-being. *J Dairy Sci*. (2006) 89:2297–308. doi: 10.3168/jds.S0022-0302(06)72301-3
10. Nielsen AC. Data warehouse for assessing animal health, welfare, risk management and -communication. *Acta Vet Scand*. (2011) 53(Suppl. 1):S3. doi: 10.1186/1751-0147-53-S1-S3
11. Hop GE, Mourits MC, Oude Lansink AG, Saatkamp HW. Simulation of cross-border impacts resulting from classical swine fever epidemics within the Netherlands and Germany. *Transbound Emerg Dis*. (2016) 63:e80–102. doi: 10.1111/tbed.12236
12. Loorbach D. Transition management for sustainable development: a prescriptive, complexity-based governance framework. *Govern Int J Policy Admin Inst*. (2010) 23:161–83. doi: 10.1111/j.1468-0491.2009.01471.x
13. Beloeil PA, Chauvin C, Proux K, Fablet C, Madec F, Alioum A. Risk factors for Salmonella seroconversion of fattening pigs in farrow-to-finish herds. *Vet Res*. (2007) 38:835–48. doi: 10.1051/vetres:2007034
14. Amass SF, Clark LK. Biosecurity considerations for pork production units. *Swine Health Prod*. (1999) 7:217–28.

15. Racicot M, Venne D, Durivage A, Vaillancourt JP. Description of 44 biosecurity errors while entering and exiting poultry barns based on video surveillance in Quebec, Canada. *Prev Vet Med*. (2011) 100:193–9. doi: 10.1016/j.prevetmed.2011.04.011
16. Hidano A, Enticott G, Christley RM, Gates MC. Modeling dynamic human behavioral changes in animal disease models: challenges and opportunities for addressing bias. *Front Vet Sci*. (2018) 5:14. doi: 10.3389/fvets.2018.00137
17. Ellis-Iversen J, Cook AJC, Watson E, Nielen M, Larkin L, Wooldridge M, et al. Perceptions, circumstances and motivators that influence implementation of zoonotic control programs on cattle farms (vol 93, pg 276, 2010). *Prev Vet Med*. (2010) 94:318. doi: 10.1016/j.prevetmed.2010.02.004
18. Roe BE. The risk attitudes of US farmers. *Appl Econ Perspect Policy*. (2015) 37:553–74. doi: 10.1093/aepp/ppv022
19. Janz NK, Becker MH. The health belief model - a decade later. *Health Educ Q*. (1984) 11:1–47. doi: 10.1177/109019818401100101
20. Ajzen I. The theory of planned behavior. *Org Behav Hum Decision Proc*. (1991) 50:179–211. doi: 10.1016/0749-5978(91)90020-t
21. Merrill SC, Koliba CJ, Moegenburg S, Zia A, Parker J, Sellnow T, et al. Decision-making in Livestock biosecurity practices amidst environmental and social uncertainty: evidence from an experimental game. *PloS ONE*. (2019) 14:e0214500. doi: 10.1371/journal.pone.0214500
22. Thaler RH, Sunstein CS, Balz JP. Choice architecture. In: Shafir, editor. *The Behavioral Foundations of Public Policy*. Princeton, NJ: Princeton University Press (2012). p. 428–39.
23. Sayers RG, Good M, Sayers GP. A survey of biosecurity-related practices, opinions and communications across dairy farm veterinarians and advisors. *Vet J*. (2014) 200:261–9. doi: 10.1016/j.tvjl.2014.02.010
24. Lipkus IM, Hollands JG. The visual communication of risk. *J Natl Cancer Inst Monogr*. (1999) 1999:149–63.
25. Slovic P, Peters E, Finucane ML, MacGregor DG. Affect, risk, and decision making. *Health Psychol*. (2005) 24:S35–40. doi: 10.1037/0278-6133.24.4.s35
26. Marx SM, Weber EU, Orlove BS, Leiserowitz A, Krantz DH, Roncoli C, et al. Communication and mental processes: experiential and analytic processing of uncertain climate information. *Glob Environ Change Hum Policy Dimen*. (2007) 17:47–58. doi: 10.1016/j.gloenvcha.2006.10.004
27. Slovic P, Finucane ML, Peters E, MacGregor DG. Risk as analysis and risk as feelings: some thoughts about affect, reason, risk, and rationality. *Risk Anal*. (2004) 24:311–22. doi: 10.1111/j.0272-4332.2004.00433.x
28. Millman C, Christley R, Rigby D, Dennis D, O'Brien SJ, Williams N. Catch 22: biosecurity awareness, interpretation and practice amongst poultry catchers. *Prev Vet Med*. (2017) 141:22–32. doi: 10.1016/j.prevetmed.2017.04.002
29. Elbers ARW, de Koeijer AA, Scolamacchia F, van Rijn PA. Questionnaire survey about the motives of commercial livestock farmers and hobby holders to vaccinate their animals against Bluetongue virus serotype 8 in 2008-2009 in the Netherlands. *Vaccine*. (2010) 28:2473–81. doi: 10.1016/j.vaccine.2010.01.047
30. Enticott G, Maye D, Carmody P, Naylor R, Ward K, Hinchliffe S, et al. Farming on the edge: farmer attitudes to bovine tuberculosis in newly endemic areas. *Vet Rec*. (2015) 177:5. doi: 10.1136/vr.103187
31. Smith VL, Walker JM. Monetary rewards and decision cost in experimental economics. *Econ Inquiry*. (1993) 31:245–61. doi: 10.1111/j.1465-7295.1993.tb00881.x
32. Smith VL. From old issues to new directions in experimental psychology and economics. *Behav Brain Sci.* (2001) 24:428–9.
33. Holt CA, Laury SK. Risk aversion and incentive effects. *Am Econ Rev*. (2002) 92:1644–55. doi: 10.1257/000282802762024700
34. Chakravarty S, Roy J. Recursive expected utility and the separation of attitudes towards risk and ambiguity: an experimental study. *Theory Decis*. (2009) 66:199–228. doi: 10.1007/s11238-008-9112-4
35. Montanaro E, Fiellin LE, Fakhouri T, Kyriakides TC, Duncan LR. Using videogame apps to assess gains in adolescents' substance use knowledge: new opportunities for evaluating intervention exposure and content mastery. *J Med Int Res*. (2015) 17:8. doi: 10.2196/jmir.4377
36. Hardy JL, Nelson RA, Thomason ME, Sternberg DA, Katovich K, Farzin F, et al. Enhancing cognitive abilities with comprehensive training: a large, online, randomized, active-controlled trial. *PloS ONE. (*2015) 10:17. doi: 10.1371/journal.pone.0134467
37. Gonzalez C, Czlonka L. Games for peace: empirical investigations with peacemaker. In: Cannon-Bowers J and Bowser C, editors *Serious Game Design and Development: Technologies for Training and Learning*. Hershey, PA: IGI Global (2010). p. 134–49.
38. Sarin R, Wieland A. Risk aversion for decisions under uncertainty: are there gender differences? *J Behav Exp Econ*. (2016) 60:1–8. doi: 10.1016/j.socec.2015.10.007
39. Choo CYL, Fonseca MA, Myles GD. Do students behave like real taxpayers in the lab? Evidence from a real effort tax compliance experiment. *J Econ Behav Org*. (2016) 124:102–14. doi: 10.1016/j.jebo.2015.09.015
40. Porter DB. Computer games: paradigms of opportunity. *Behav Res Methods Instr Comput*. (1995) 27:229–34. doi: 10.3758/bf03204737
41. Boyle EA, Hainey T, Connolly TM, Gray G, Earp J, Ott M, et al. An update to the systematic literature review of empirical evidence of the impacts and outcomes of computer games and serious games. *Comput Educ*. (2016) 94:178–92. doi: 10.1016/j.compedu.2015.11.003
42. Cheong L, Bleisch S, Kealy A, Tolhurst K, Wilkening T, Duckham M. Evaluating the impact of visualization of wildfire hazard upon decision-making under uncertainty. *Int J Geogr Inform Sci*. (2016) 30:1377–404. doi: 10.1080/13658816.2015.1131829
43. Noremark M, Lewerin SS, Ernholm L, Frossling J. Swedish farmers' opinions about biosecurity and their intention to make professionals use clean protective clothing when entering the stable. *Front Vet Sci*. (2016) 3:46. doi: 10.3389/fvets.2016.00046
44. Kahneman D, Tversky A. Prospect theory - analysis of decision under risk. *Econometrica*. (1979) 47:263–91. doi: 10.2307/1914185
45. Yi R, Gatchalian KM, Bickel WK. Discounting of past outcomes. *Exp Clin Psychopharmacol*. (2006) 14:311–7. doi: 10.1037/1064-1297.14.3.311
46. Caruso EM, Gilbert DT, Wilson TD. A wrinkle in time - asymmetric valuation of past and future events. *Psychol Sci*. (2008) 19:796–801. doi: 10.1111/j.1467-9280.2008.02159.x
47. Buhrmester M, Kwang T, Gosling SD. Amazon's mechanical turk: a new source of inexpensive, yet high-quality, data? *Perspect Psychol Sci*. (2011) 6:3–5. doi: 10.1177/1745691610393980
48. Warner KE. Need for some innovative concepts of innovation: an examination of research on the diffusion of innovations. *Policy Sci*. (1974) 5:433–51. doi: 10.1007/bf00147229
49. Levinthal DA, March JG. The myopia of learning. *Strat Manage J*. (1993) 14:95–112. doi: 10.1002/smj.4250141009
50. Bates D, Machler M, Bolker BM, Walker SC. Fitting linear mixed-effects models using lme4. *J Stat Softw*. (2015) 67:1–48. doi: 10.18637/jss.v067.i01
51. R Development Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Vienna: R Foundation for Statistical Computing (2018). Available online at: http://www.R-project.org (accessed May 15, 2019)
52. Burnham KP, Anderson DR. *Model Selection and Multimodel Inference: The Practical Information Theoretic Approach*. New York, NY: Springer (2002).
53. Burnham KP, Anderson DR. Multimodel inference - understanding AIC and BIC in model selection. *Sociol Methods Res*. (2004) 33:261–304. doi: 10.1177/0049124104268644
54. Patt AG, Schrag DP. Using specific language to describe risk and probability. *Clim Change*. (2003) 61:17–30. doi: 10.1023/a:1026314523443
55. Lipkus IM. Numeric, verbal, and visual formats of conveying health risk: suggested best practices and future recommendations. *Med Decis Making*. (2007) 27:696–713. doi: 10.1177/0272989x07307271
56. Visschers VHM, Meertens RM, Passchier WWF, de Vries NNK. Probability information in risk communication: a review of the research literature. *Risk Anal*. (2009) 29:267–87. doi: 10.1111/j.1539-6924.2008.01137.x
57. Crane TA, Roncoli C, Paz J, Breuer N, Broad K, Ingram KT, et al. Forecast skill and farmers' skills: seasonal climate forecasts and agricultural risk management in the Southeastern United States. *Weather Clim Soc*. (2010) 2:44–59. doi: 10.1175/2009wcas1006.1
58. Moser SC. Communicating adaptation to climate change: the art and science of public engagement when climate change comes home. *Wiley Interdisc Rev Clim Change*. (2014) 5:337–58. doi: 10.1002/wcc.276
59. Ahmed H, Naik G, Willoughby H, Edwards AGK. Communicating risk. *BMJ Br Med J*. (2012) 344:7. doi: 10.1136/bmj.e3996

60. Zia A, Koliba CJ, Merrill SC, Bucini G, Clark E, Wiltshire S, et al. Identifying leverage points for biosecurity risk management using massive online games and agent-based models. In: *Conference on Complex Systems*, Thessaloniki (2018).
61. AASV. *Porcine Epidemic Diarrhea Virus (PEDv)*. American Association of Swine Veterinarians (2018). Available online at: https://www.aasv.org/Resources/PEDv/PEDvWhatsNew.php (accessed December 18, 2018).
62. Camerer C, Weber M. Recent developments in modeling preferences - uncertainty and ambiguity. *J Risk Uncertainty*. (1992) 5:325–70. doi: 10.1007/bf00122575
63. Lipshitz R, Strauss O. Coping with uncertainty: a naturalistic decision-making analysis. *Org Behav Hum Decision Proc*. (1997) 69:149–63. doi: 10.1006/obhd.1997.2679
64. Trope Y, Liberman N. Temporal construal. *Psychol Rev*. (2003) 110:403–21. doi: 10.1037/0033-295x.110.3.403
65. Sellnow DD, Lane DR, Sellnow TL, Littlefield RS. The IDEA model as a best practice for effective instructional risk and crisis communication. *Commun Stud*. (2017) 68:552–67. doi: 10.1080/10510974.2017.1375535
66. Weber EU, Johnson EJ. Mindful judgment and Decision Making. *Ann Rev Psychol*. (2009) 60:53–85. doi: 10.1146/annurev.psych.60.110707.163633
67. Sunstein CS, Thaler RH. *Nudge: Improving Decisions about Health, Wealth, and Happiness*. New Haven, CT: Yale University Press (2008).
68. Thaler RH. Towards a positive theory of consumer choice. *J Econ Behav Org*. (1980) 1:39–60.

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Framework for Estimating Indirect Costs in Animal Health Using Time Series Analysis

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Traditionally, cost-benefit analyses (CBAs) focus on the direct costs of animal disease, including animal mortality, morbidity, and associated response costs. However, such approaches often fail to capture the wider, dynamic market impacts that could arise. The duration of these market dislocations could last well after an initial disease outbreak. More generally, current approaches also muddle definitions of indirect costs, confusing debate on the scope of the totalities of disease-induced economic impacts. The aim of this work was to clarify definitions of indirect costs in the context of animal diseases and to apply this definition to a time series methodological framework to estimate the indirect costs of animal disease control strategies, using a foot and mouth disease (FMD) outbreak in Scotland as a case study. Time series analysis is an econometric method for analyzing statistical relationships between data series over time, thus allowing insights into how market dynamics may change following a disease outbreak. First an epidemiological model simulated FMD disease dynamics based on alternative control strategies. Output from the epidemiological model was used to quantify direct costs and applied in a multivariate vector error correction model to quantify the indirect costs of alternative vaccine stock strategies as a result of FMD. Indirect costs were defined as the economic losses incurred in markets after disease freedom is declared. As such, our definition of indirect costs captures the knock-on price and quantity effects in six agricultural markets after a disease outbreak. Our results suggest that controlling a FMD epidemic with vaccination is less costly in direct and indirect costs relative to a no vaccination (i.e., "cull only") strategy, when considering large FMD outbreaks in Scotland. Our research clarifies and provides a framework for estimating indirect costs, which is applicable to both exotic and endemic diseases. Standard accounting CBAs only capture activities in isolation, ignore linkages across sectors, and do not consider price effects. However, our framework not only delineates when indirect costs start, but also captures the wider knock-on price effects between sectors, which are often omitted from CBAs but are necessary to support decision-making in animal disease prevention and control strategies.

Keywords: indirect costs, animal disease, foot and mouth disease, time series modeling, vector error correction model, market impact, disease control strategy

INTRODUCTION

Animal diseases represent threats to the environment, animal welfare, public health, and the economy. Livestock diseases contribute to losses via increased mortality, reduced productivity, control costs, loss in trade, decreased market value, and food insecurity (1). The economic and social impacts of livestock disease have been recognized globally, in both developed and developing countries (2). Quantifying the economic impact of an animal disease outbreak is important in support of prevention and control decisions for improved animal health.

The economic costs of animal disease can be categorized as either direct or indirect losses.

Over the last decade, the direct cost of zoonotic diseases has been estimated at more than $20 billion and indirect losses at over $200 billion to affected economies as a whole (3). This highlights that indirect costs are an important aspect of the economic impact of an animal disease outbreak, and as these estimates suggest, can be larger in magnitude than direct costs (3–5). While direct disease costs are important, indirect costs are also of concern (6) because the costs of disease do not stop at the farm-gate, within the agricultural sector, or after disease-freedom is declared. Disease can affect a wide range of sectors of the economy including rural business and tourism (7). However, few studies evaluate the full economic cost of disease outbreaks (8). Often only farm costs are considered and indirect impacts are not included (9, 10). There is a danger that estimates of economic costs of animal disease fail to capture indirect costs and may underestimate the true costs of an outbreak. It is important to understand the full economic cost of animal disease outbreaks, and to achieve this, economic disease cost frameworks must include indirect costs. This is essential to support holistic decision-making of disease prevention and control strategies because producers and policymakers need to be aware of the broader disease impacts to improve animal health welfare strategies and policy. This will be particularly important if alternative policy options lead to significantly different indirect cost outcomes and hence different decision choices than would otherwise be indicated.

At the same time, even where indirect costs are considered in the analysis, the definitions of direct and indirect costs of animal disease outbreaks vary in the literature (as described in **Table 1**). Some studies do not categorize economic costs as either direct or indirect, while others do not explicitly define direct and indirect costs (17). This non-exhaustive summary table highlights the inconsistency in the definition of direct and indirect costs making it difficult to quantify and compare the economic impact of livestock diseases. In particular, prevention and control costs are allocated as either direct or indirect costs, depending on the individual interpretation. The distinction between direct and indirect economic losses of animal diseases is unclear and subjective. Often there are a lack of data and an analytical framework to capture indirect costs. Hence, there is a need for a more systematic and unified framework on which to estimate and assess the economic impact of animal diseases (18). It is important to categorize direct and indirect costs more objectively to help determine who the economic impact of alternative animal disease scenarios likely fall upon.

A country's animal disease status changes over time. For this reason, we assume direct costs are the sum of losses from the first confirmation of a notifiable disease outbreak until disease freedom is declared (19). Accordingly, indirect costs are defined as the economic loss incurred in affected commodity markets (e.g., domestic and international trade) and in other sectors (e.g., tourism) *after* disease freedom is declared. Applying this definition, indirect costs are related to knock-on effects (i.e., shocks) in markets as a result of changes in prices and quantities for producers and/or consumers, which can also be described as revenue foregone, after disease freedom. Using disease status as a marker, our definition of indirect costs objectively differentiates when direct costs end and indirect costs begin to avoid double counting.

A range of models are available for assessing the economic cost of livestock diseases (20). Based on our definition, indirect effects capture the substitution and displacement in markets as a result of changes to price and output in agriculture and tourism sectors (7). Capturing such dynamics is challenging and there is a need for models that encapsulate the impacts of a disease outbreak in multiple agricultural markets and linkages with non-agricultural sectors (21). Traditional cost benefit analyses (CBAs) based on farm accounts and partial budgets cannot capture such dynamics, and as such partial equilibrium (PE) (4, 22–24) and computable general equilibrium (CGE) (7, 25, 26) models are being used to

TABLE 1 | Non-exhaustive literature review summary of the definitions of direct and indirect components of animal disease costs.

Direct costs	Indirect costs	Source
Visible production losses (e.g., death, lower yield, and reduced growth) and invisible losses (e.g., reduced fertility and changes to herd structure) losses	Disease control costs Revenue foregone from restricted market access	(11)
Disease control costs	Export losses	(12)
Disease detection, confirmation, and control costs	Revenue foregone from trade restrictions Production losses beyond the agricultural sector Farmer losses taking into account market value and compensation received	(13)
Loss in profitability	Disease control costs	(14)
Disease losses that are experienced at the herd level on farm	Public expenditures and losses that occur beyond the farmgate	(9)
Disease control and prevention costs	Export losses	(4)
Losses to agriculture, the food industry, the public sector, and consumers	Losses to other sectors in the supply chain and tourism	(15)
Disease management and carcass disposal costs	Net economic welfare of the disease to producers, processors, and consumers.	(16)

estimate the indirect knock-on effects of animal disease. A PE model is based on supply and demand relationships to evaluate the impact of a shock, such as a disease outbreak, on one sector of the economy assuming the rest of the economy is fixed. This approach is thus simplified and ignores any sector interactions. On the other hand, CGE models simulate how a multi-sector economy might respond to a shock until equilibrium is restored, with linkages between different sectors. While CGE models link multiple sectors and can represent the entire economy they also rely on economic data and in some cases estimates of elasticities[1] to parameterize market responses. Hence, a weakness of these models is a reliance on estimates of elasticities which are often outdated or "guesstimated," if available at all, which might affect the model's performance and estimation. Therefore, in the absence of good data or if elasticities cannot be estimated, demand and supply relationships are based on assumptions.

An alternative and complementary approach to PE and CGE modeling is times series analysis. Time series modeling (27) is an econometric method for identifying patterns and representing statistical relationships between data series ordered over time, and forecasting to predict using observed data. Time series models have been cited extensively in the literature including in the disciplines of economics, mathematics, epidemiology, finance, meteorology, engineering, and natural sciences to name just a few. However, their application in estimating the cost of animal disease is somewhat limited (28, 29). In these examples, time series models have estimated the impact that a disease outbreak is likely to have on markets. The type of time series model selected depends on the underlying statistical properties of the data (30). Time series models assume data are stationary, such that the mean, variance, and autocorrelation structure do not change over time. Stationary properties of the data define which time series model to use. Vector autoregressive (VAR) models (31) are a multivariate generalization of a univariate autoregressive model, in which each variable is a linear function of past values of itself and other variables. Alternatively, autoregressive distributed lag models (32) are based on regression equations to predict using current and past values of time series. When cointegration is detected, i.e., long-run relationship between variables, a vector error correction model (VECM) is the most appropriate model to represent the data. A VECM estimates long-run equilibrium relationships and short-run dynamics between data series over time (33). Impulse response functions (IRFs) (34) are a useful tool for forecasting and determining the relationship between variables over time until a shock dissipates. An IRF describes the change in a variable over a time after a shock in another variable. IRFs lend themselves to modeling a disruption to supply chain shock, i.e., animals culled following an outbreak, and simulating the response of such a shock in other variables. Once obtained, IRF coefficients can be interpreted as elasticities (35) on which to estimate price and quantity changes for estimating indirect costs, i.e., the economic losses incurred in markets after disease freedom is declared.

[1]Elasticity measures the extent to which a proportional change in one variable is associated with a proportional change in another variable.

The culling of animals for disease control reduces their supply, disrupting domestic meat production. Economic theory assumes that the slaughter of animals will lead to a supply shortage affecting producers and consumers by increasing the prices consumers pay for commodities (36). During an exotic disease outbreak, an export ban would be triggered which is likely to put downward pressure on prices as meat destined for export would remain within domestic markets. While this might be the case during an outbreak, what will happen in markets after disease freedom is declared and how much prices and quantities will adjust by? Time series analysis can help with this, using market data, to estimate such price and quantity changes, i.e., market response, without relying on estimates of elasticities from the literature. Hence, a more data-focused time series model can capture the relationship between prices and substitution effects between markets to compliment and feed into more comprehensive yet computationally demanding assumption-based models, such as CGE models, which rely on good data from existing literature.

The overall aim of this work was to outline the steps necessary to estimate indirect costs, i.e., the economic losses incurred in markets after disease freedom is declared using a time series model. We apply this in the context of a modeled Foot and Mouth Disease (FMD) in Scotland. FMD is considered one of the most economically significant livestock diseases globally due to its impact on production, as a barrier to international trade and high control/stamping out costs (8). While the direct costs of FMD in Scotland have been estimated, there is a need for indirect costs to also be estimated (19). Therefore, our paper seeks to remedy this by estimating the indirect costs of a hypothetical FMD outbreak in six of Scotland's important agricultural commodity markets, (i.e., beef, pork, lamb, chicken, milk, and feed wheat), and, by this provide a more objective definition of indirect costs using a time series modeling framework. We considered agricultural commodity markets that were thought to be most affected by an FMD outbreak. The indirect economic impacts are likely to be felt much more widely than this study attempts to quantify.

While FMD is likely to affect international trade and tourism, the data to support such analysis are not available at an appropriate resolution. Hence, our paper focusses on the domestic supply side evaluating indirect costs incurred by producers after a disease outbreak is over as an illustration of the method. The distribution of indirect costs was compared to direct costs on alternative FMD control strategies in Scotland. We assess the potential impact of vaccine stock scenarios on indirect costs on decision outcomes in a future outbreak and so the suitability of time series for contribution to decision support. Vaccine capacity is important (37, 38) and vaccination plays a key role in large outbreaks of FMD in terms of the epidemiological benefit (39) and direct economic costs (19). Hence, this paper evaluates the indirect costs of alternative levels of vaccines stocks to compliment previous work (19). Our indirect cost estimation framework can be applied to other animal disease outbreaks in Scotland, the UK or elsewhere. The paper provides insights into an econometric method which quantifies broader knock-on effects of notifiable animal disease that affect production and trade after an outbreak is over which are often overlooked.

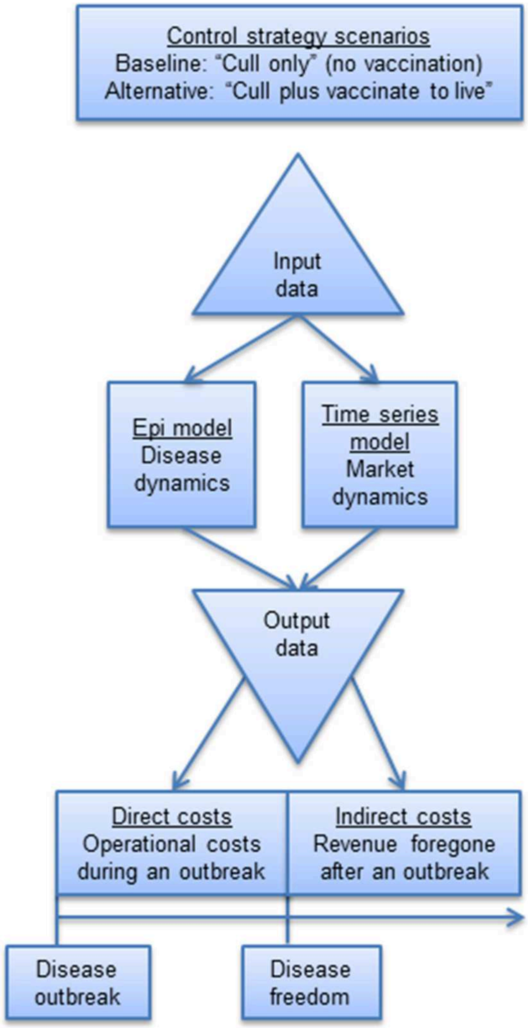

FIGURE 1 | Economic cost modeling framework.

MATERIALS AND METHODS

Our indirect cost methodology was demonstrated in the context of a FMD outbreak in Scotland. The indirect cost modeling framework (**Figure 1**) for estimating indirect costs involved the following four steps: (i) collection of input data; (ii) selection and specification of a time series model to simulate market dynamics; (iii) simulation of disease dynamics by way of an epidemiological model; and (iv) estimation of indirect costs based on integrating output from the time series model and epidemiological model under alternative disease control strategies. This methodological framework is described below.

Overview of Foot and Mouth Disease

FMD is a highly contagious viral disease affecting ruminants, including cows, sheep and pigs. Globally, FMD is estimated to cost endemic countries between $6.5 and $21 billion annually, due to visible production losses and vaccination costs in endemic countries (8). In addition, previously disease-free countries incurred outbreak costs of between $0.5 billion and $10 billion following an outbreak, i.e., between 0.2 and 0.6% of GDP (8). These losses make FMD one of the most economically important livestock diseases. In the UK, FMD is a notifiable exotic disease, with the last outbreak in 2007 estimated to have cost the British livestock sector over £100 million and the government £47 million (40). However, a larger, costlier outbreak occurred in 2001 generating losses of over £8 billion (41). During the 2001 outbreak, the first case of FMD was confirmed on 20 February and the disease was eradicated by the end of September 2001, by which time more than 6 million animals were slaughtered (41).

Animal health and welfare is a devolved issue in the UK, meaning the Scottish Parliament and Scottish Government have responsibility for the health and welfare of animals in Scotland. FMD is a notifiable disease and control mechanisms include movement bans and restrictions of the marketing of milk and meat products during an outbreak. The principal control method to eradicate FMD, as required under EU and national law, is the slaughter of affected animals (i.e., infected animals and dangerous contacts) to prevent any further spread of the virus. Vaccination is also an important tool in controlling FMD during an outbreak. However, preventative vaccination is banned under EU law, but the Scottish Government considers emergency vaccination a disease control strategy during an outbreak (42). The presence of a notifiable exotic disease, such as FMD, will result in the UK losing its FMD disease freedom status and trigger an export ban until disease freedom is declared. The loss of export trade may persist beyond disease freedom should importing countries adopt a precautionary approach.

Data Collection

Monthly agriculture commodity price and quantity data between January 2004 and December 2016 ($n = 156$ observations) were gathered from various sources for this study (see **Table 2**). Producer prices were adjusted for inflation using the producer price index (47) to reflect real prices in 2011, the year in which the modeled hypothetical FMD outbreak occurred. Some data series were only available at either the UK or Great Britain level, consequently these data were adjusted to reflect Scottish prices or Scotland's share of the UK's or Great Britain's volume of production. The prices of UK pork, lamb, chicken, milk, and feed wheat were adjusted by 0.99 to reflect prices in Scotland relative to UK levels (48). Wholesale milk production was adjusted to reflect Scotland's share of the UK's milk production (49). Scotland's production of feed wheat was also adjusted to reflect Scotland's share of Great Britain's production (50). Scottish cattle, pig and lamb slaughtered in Scotland was adjusted to reflect Scottish livestock slaughtered in the rest of the UK (i.e., beef: 5%, pig; 55%, lamb: 15%) (51).

Scotland was assumed to be a closed economy in terms of economic impacts on domestic supply because trade (i.e., exports and import) data were not available at an appropriate monthly resolution to determine the indirect cost after disease freedom is declared. Consumer demand was assumed not to be affected because FMD is not a zoonosis and there was not sufficient model power to include retail market data series.

TABLE 2 | Description of monthly price and quantity data series.

Data series (*Acronym*)	Description of data	Units	References
Price of beef (*PBeef*)	Average monthly farmgate price of Scottish steers (deadweight price)	£ Per ton	(QMS 2017, personal communication, 20 October)
Price of pork (*PPork*)	Average monthly farmgate price of pork in the UK (deadweight price)	£ Per ton	(QMS 2017, personal communication, 20 October)
Price of lamb (*PLamb*)	Average monthly farmgate price of lamb in the UK (deadweight price)	£ Per ton	(QMS 2017, personal communication, 20 October)
Price of chicken (*PChicken*)	Average monthly wholesale price of chicken in the UK (roasters 2050g and under 2450g)	£ Per ton	(Defra 2017, personal communication, 1 September)
Price of milk (*PMilk*)	Average monthly farmgate price of milk in UK	£ Per liter	(43)
Price of feed wheat (*PWheat*)	Average monthly farmgate price of feed wheat in the UK	£ Per ton	(44)
Quantity of cattle (*QCattle*)	Quantity of cattle (including finished and culled cattle) of Scottish origin slaughtered (carcase weight)	Ton	(Scottish Government 2017, personal communication, 3 October)
Quantity of pig (*QPig*)	Quantity of pigs (including sows and boars) of Scottish origin slaughtered (carcase weight)	Ton	(Scottish Government 2017, personal communication, 3 October)
Quantity of sheep (*QSheep*)	Quantity of sheep (including lambs and ewes) of Scottish origin slaughtered (carcase weight)	Ton	(Scottish Government 2017, personal communication, 3 October)
Quantity of chicken (*QChicken*)	Quantity of poultry of Scottish origin slaughtered (carcase weight)	Ton	(Scottish Government 2017, personal communication, 3 October)
Quantity of milk (*QMilk*)	Quantity of wholesale milk produced in the UK	Liters	(45)
Quantity of feed wheat (*QWheat*)	Quantity of Scottish feed wheat (animal feeding stuff) production in Great Britain	Ton	(46)

Time Series Model Selection

A time series model was used to quantify the indirect costs, i.e., the economic losses incurred in markets after disease freedom is declared, in domestic commodity markets associated with an FMD outbreak in Scotland. The steps for selecting the most appropriate time series model are presented in **Figure 2** [Adapted from Wooldridge (52), Johnston and DiNardo (53)]. Following data gathering and transformation, the order to which data series are integrated and the presence of cointegration determines the times series model selected. In our case, a VECM was selected and an IRF evaluated market dynamics resulting from a hypothetical outbreak for the estimation of indirect costs.

Data Exploration and Processing

Descriptive statistics and plotting were used to summarize and visualize the characteristics and patterns in the data series, including the presence of seasonal variation. Seasonal adjustments were performed by estimating and removing seasonality from the data to understand underlying trends and movement in the data over time, masked by seasonal variation (54–57). Data were expressed in natural logarithms to ensure the series were on a consistent scale.

Following the methodological framework (**Figure 1**), data series were decomposed into seasonal, trend, and residual components (**Figure S1**). The seasonally decomposed data series suggest that the pattern of seasonality is similar across months for each variable. Therefore, seasonality was removed additively before modeling the data. Following removal of seasonality, data were expressed in natural logs to ensure the series were on a consistent scale.

Testing of Stationarity and Cointegration

Stationarity is an underlying statistical property of data required for time series analysis. A stationary process is such that the mean, variation, and autocorrelation in the structure of the data do not change over time. A trend in the mean due to the presence of a unit root or deterministic trends are causes that violate the underlying assumption of stationarity.

The data series were tested for stationarity (i.e., the presence of unit roots) using the augmented Dickey-Fuller [ADF; (58)] test to detect the order of integration, a metric describing a unit root process in time series analysis. A time series, Y_t, is integrated of order 0, or at the level, if $\mathrm{Y}_t \sim I\,(0)$ is stationary. Y_t is integrated of order 1, denoted by $I[1]$, if it is not stationary but the first difference (i.e., $Y_t - Y_{t-1}$) of the series is stationary. If Y_t is non-stationary, but $Y_t \sim I\left(\mathrm{d}\right)$ such that $d > 0$ is stationary, then the data series is integrated of order d. Agricultural commodity market data are assumed to be stationary but typically such data exhibit non-stationary behavior (59).

Examining the stationary process of the data and cointegration between the time series will determine with which model to analyse the data [**Figure 2**: Adapted from Wooldridge (52) and Johnston and DiNardo (53)]. Cointegration is a statistical property that identifies long-run relationships between data series. Data series are cointegrated if all the series are integrated of order 1, (i.e., $I(1)$) and a linear combination of

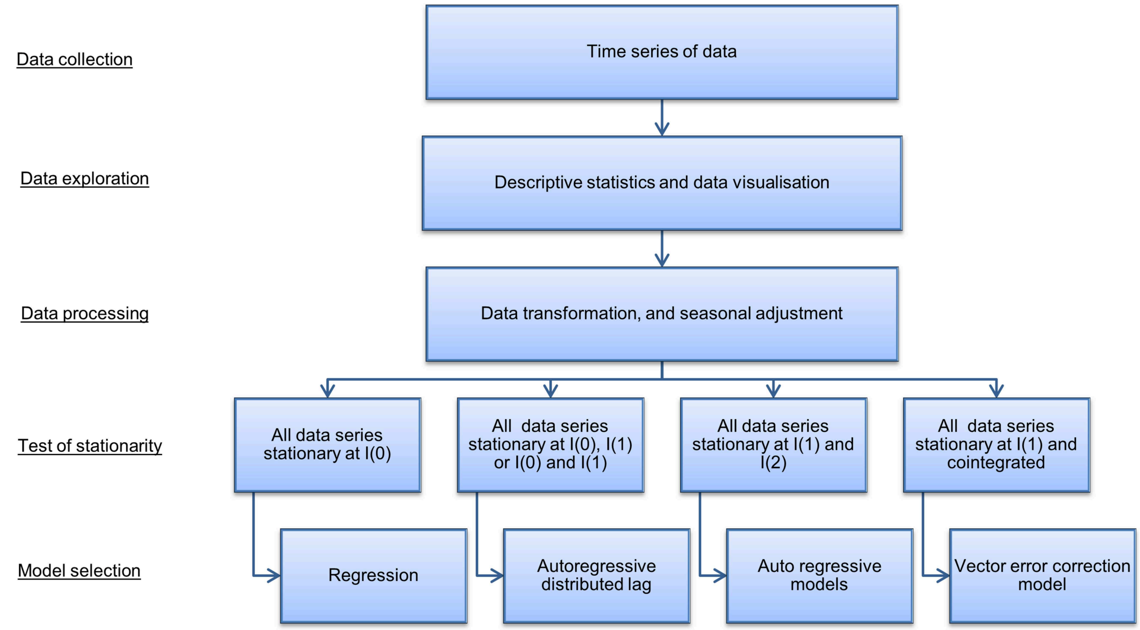

FIGURE 2 | Summary of steps in time series model selection. Source: Adapted from Wooldridge (52) and Johnston and DiNardo (53).

these series are integrated of order 0 (i.e., $I(0)$). If cointegration is present, this suggests there is an equilibrium relationship in the long-run, although the series may diverge from that equilibrium in the short-run. Johansen's trace test (33) is a statistical procedure to determine whether two or more $I(1)$ time series are cointegrated. The Johannsen's trace test was used because it is robust to skewness and excess kurtosis. In the case that cointegration is present a vector error correction model is selected, which models both short and long-run relationships jointly in multiple data series. In cases where no cointegration is detected alternative models, such as autoregressive and autoregressive distributed lag models, are appropriate [**Figure 2**: Adapted from Wooldridge (52) and Johnston and DiNardo (53)].

Model Selection

Statistical testing for stationarity and cointegration described above and outlined in **Figure 2** [Adapted from Wooldridge (52) and Johnston and DiNardo (53)] identified that a VECM model was appropriate. The Results section describes the outcome of the statistical testing. A VAR model of order p (where p is the number of lags), or a VAR(p), combined with an error correction model can be modeled as a VECM with $p-1$ lags, i.e., VECM($p-1$) (33). According to the Granger theorem (60–62), a general multivariate VECM($p-1$) with K endogenous variables, an intercept, u, and time trend, δt, takes the form:

$$\Delta Y_t = \mu + \delta t + \sum_{l=1}^{p-1} \Gamma_l \Delta Y_{t-l} + \prod Y_{t-1} + \varepsilon_t \qquad (1)$$

where, Y_t is a $K \times 1$ vector of K $I(1)$ endogenous variables such that the first difference is $Y_t = Y_t - Y_{t-1}$. The number of lags is denoted by l (where, $l = 1, \ldots, p-1$) and t is the time period. u is a $K \times 1$ parameter vector associated with the intercept and δ is a $K \times 1$ parameter vector associated with a time trend, t. The deterministic regressors, u and δ contribute to both the short and long-run components of Y_t. Γ_l is a $K \times K$ matrix of short-run dynamic adjustment coefficients at lag $p-1$ of Y_{t-l}. $\prod$ is a $K \times K$ error correction matrix and the long-run equilibrium relationship among Y_t is determined by the rank, r. The matrix $\prod$ contains long-run relationships assuming there is a reduced rank of $0 \leq r \leq K$ it follows that $\prod = -\alpha\beta'$. The strength of cointegrating relationships is determined by α and β'. Where, α is a $K \times r$ matrix of speed of adjustment to equilibrium coefficients of which K variables adjust to error correction terms at varying speeds and β' is a $r \times K$ matrix of long-run cointegration coefficients. ε_t is a $K \times 1$ vector of independently and identically distributed errors over time with a mean of 0 and covariance matrix, Σ_ε. Following this, a VECM($p-1$) in (1) can be written as:

$$\begin{aligned} \Delta Y_t &= \mu + \delta t + \Gamma_1 \Delta Y_{t-1} + \Gamma_2 \Delta Y_{t-2} + \ldots \\ &+ \Gamma_{p-1} \Delta Y_{t-(p-1)} + \alpha\beta' Y_{t-1} + \varepsilon_t \end{aligned} \qquad (2)$$

where, $\Gamma_j = -\sum_{j=l+1}^{p} \prod_j$. Based on the VECM($p-1$) (2), an IRF was estimated to evaluate how 12 endogenous variables (i.e., *PBeef*, *PPork*, *PLamb*, *PChicken*, *PMilk*, *PWheat*, *QCattle*, *QPig*, *QSheep*, *QChicken*, QMilk, and *QWheat*) responded to 3 impulses, or shocks, (i.e., *QCattle*, *QPig* and *QSheep*) at a particular point in time and subsequent periods. An IRF gives the response of the kth variable when a system is shocked by one standard-deviation in the jth variable, and the matrix ψ allows for alternative responses in different variables. When data are expressed in natural logarithms, the IRF coefficients represent the percentage change in the *k*th variable when the system is shocked by a 1% change in the *j*th variable. As such, the values of IRF coefficients are interpreted as elasticities, namely IRF elasticities. The IRF estimates the response of endogenous variable *k*, $Y_{k,t+n,}$ to a one-time impulse, or shock, in variable *j*, $Y_{j,\, t}$, from time t to time $t + n$. Where, n = 0,..., N is the number of time periods specified over which the endogenous response variable evolves with all other endogenous variables at time t or earlier held constant. The IRF is expressed as:

$$Y_{k,\ t+n} = \sum_{i=0}^{\infty} \psi_i \varepsilon_{t+n-i} \quad (3)$$

$$\{\psi_n\}_{k,\, j} = \frac{\delta Y_{k,t+n}}{\delta \varepsilon_{j,t}} \quad (4)$$

where, $Y_{k,\ t+n}$ is a function of current and lagged impulses, or shocks, and accordingly an IRF represents the adjustment process and impacts of a shock over time. The coefficients in ψ_{kj} are the impulse response functions, where ψ is a $n\ x\ k$ matrix of j matrices depending on the number of response variables, $Y_{k,\, t}$, impulses, $Y_{j,\, t}$, and n, the number of specified time periods over which the response variables evolve and time periods after which the impulse dissipates, *i*. A generalized IRF assumes that a shock occurs at a single point in time such that shocks in different variables are independent and invariant to the ordering of variables (34). If correlation between the error terms is detected it suggests that a shock in one variable is likely to be accompanied by a shock in another variable and an orthogonalized IRF is used to model structural shocks.

Epidemiological Model

We used the Warwick FMD model to simulate the spread of FMD following a hypothetical introduction in Scotland in June 2011 and simulate various scenarios of vaccination (19). This model is a fully stochastic, spatial, farm-based model that was developed and used during the FMD epidemic in 2001 in Great Britain (63–67) and was later modified to represent the Scottish livestock industry (39). Although transmission of FMD is restricted to all farms with cattle, sheep or both, disease control activities implemented in the model will involve farms showing at least one animal susceptible (including pigs and deer). The model further assumes FMD individuals will pass through four epidemiological states: susceptible; infected, but not infectious; infectious; or reported infected and thereby culled. Following the introduction of the virus in a given *j*th premises, the model assumes that each *i*th premises is infected with a daily probability M_i depending on its own susceptibility S_i and on the transmissibility T_j of the surrounding *j* premises such that:

$$M_i = 1 - \exp\left(-S_i \sum_{i \neq j} T_j K\left(d_{ij}\right)\right)$$

where S_i and T_i depend on the species (i.e., cattle and sheep) and on the related herd size on premises (63–67). The component $K\left(d_{ij}\right)$ is the so-called "transmission kernel function" and determines the scaling factor on the rate at which infected premises may infect susceptible ones as a function of inter-farm distance d_{ij}.

A baseline scenario of a "cull only" (i.e., no vaccination) vs. alternative scenarios of "cull plus vaccinate to live" policy was simulated. The availability of vaccine stocks at the start of an outbreak was considered assuming only cattle were vaccinated and that vaccinated animals would become immune to infection after 4 days (42). As in previous work (19, 39), we made the conservative assumption that during this 4-day delay, all cattle are completely susceptible and if infected, the disease progresses in the same way as for non-vaccinated cattle. We also considered that not all cattle present on vaccinated farms would become totally immune, with 10% of the cattle remaining totally susceptible to infection and able to transmit the virus to farms that were not vaccinated (65). In line with current regulations in place in Scotland, we assumed that the vaccination campaign would start 14 days after the disease is first detected, allowing the decision to vaccinate to be taken, the doses of vaccine to be received from the appropriate vaccine bank and vaccination teams to be mobilized and actively deployed in the field. Once the decision to vaccinate has been made, vaccination would be implemented within a 10-km-radius buffer around each IP and carried out within the recommended 24 h (42).

The model simulated the effects of the Scottish Government's FMD contingency plan under alternative vaccine stock scenarios (i.e., initial vaccine stocks ranged from 100,000 to 5 million doses as in Porphyre et al. (19). Briefly, we considered that, for each vaccine stock scenario, 10,000 epidemics were simulated assuming that FMD is introduced in a single susceptible herd and spread silently to four additional herds due to delays in detecting new incursion events. Although we arbitrarily considered that outbreaks will be initiated with five infectious premises, this was based on the fact that: (1) it is unlikely for cattle farms to remain undetected for long period of time given the high awareness of farmers to the disease in the UK due to the traumatic experience during the 2001 outbreak; (2) the noticeable symptoms of FMD infection in cattle (68) and; (3) the implementation of the standstill regulations which would limit the spread of FMD due to animal movement (69). As such, the spread of FMD is likely to be mostly driven by local spread and affect a relatively small number of farms within a short period. Over all simulations, we used the same set of all initially infected herds. These were located in the county of Ayrshire, which has a high density of premises and animals, and has been previously identified as an area where there is potential for extensive initial spread (39), and hence represent the worst case scenario for FMD spread in Scotland.

Output data from the epidemiological model included the number of animals (i.e., cattle, pigs, and sheep) culled for disease control purposes, which informed the estimation of indirect costs. Direct economic costs, i.e., the economic losses incurred in markets before disease freedom is declared, were estimated from the epidemiological model data and are published (19).

Indirect Cost Estimation

The indirect costs, i.e., the economic losses incurred in markets after disease freedom is declared, associated with a FMD outbreak in Scotland were estimated by integrating output from the time

TABLE 3 | Summary statistics of monthly agriculture commodity price and quantity data between January 2014 and December 2016 (n = 156 observations).

Data series (units)	Minimum	Maximum	Median	Mean	Standard deviation	Coefficient of variation
Price of beef (£ per ton)	2,446	3,870	3,132	3,126	400.32	0.128
Price of pork (£ per ton)	1,096	1,667	1,401	1,400	114.34	0.082
Price of lamb (£ per ton)	2,317	5,476	3,711	3,694	566.18	0.153
Price of chicken (£ per ton)	928	1,681	1,347	1,341	140.27	0.105
Price of milk (£ per liter)	0.20	0.32	0.26	0.26	0.03	0.109
Price of feed wheat (£ per ton)	78	207	117	129	36.18	0.281
Quantity of cattle (ton)	12,034	19,226	14,996	15,353	1,746.00	0.114
Quantity of pig (ton)	1,679	7,246	4,580	4,230	1,502.50	0.355
Quantity of sheep (ton)	2,073	9,048	5,376	5,319	1,429.50	0.269
Quantity of chicken (ton)	1,841	11,337	6,868	6,892	2,017.50	0.293
Quantity of milk (ton)	92,533,221	131,099,341	106,746,572	107,461,126	7,978,941.54	0.074
Quantity of feedwheat (ton)	4,282	41,042	16,139	16,510	7,560.56	0.458

series model (i.e., IRF elasticities) and epidemiological model (i.e., number of animals culled inputs into the indirect costs time series model).

The IRF elasticities capture the changes in the levels of prices and quantities in six commodity markets (i.e., beef, pork, lamb, chicken, milk, and feed wheat) following the culling of 1% of animals (i.e., cattle, pig, and sheep). The IRF elasticities capture the adjustment of prices and quantities to a long-run equilibrium until the effect of the shock dissipates over time. We identified the period in which the impact of the shock dissipated, i.e., the change in the IRF elasticities tended to zero. This determines up to what period to sum the IRF elasticities to quantify the total economic impact of the animals culled.

To estimate the total impact of the supply shock, the IRF elasticities were multiplied by the epidemiological shock (i.e., number of animals culled as output from the epidemiological model) as a proportion of the national production herd [1,803,937 cattle; 389,995 pigs; and 6,801,134 sheep in June 2011; (70)]. As a result, the IRF elasticities reflect the total economic impact of a supply shock taking into account the size of the outbreak in terms of animals culled.

The indirect costs, IC_s, of alternative vaccination strategies, S, and six domestic commodity markets (i.e., beef, pork, lamb, chicken, milk, and feed wheat), i, were estimated. The indirect costs are associated with price and quantity changes, i.e., change in revenue or revenue foregone, in each market, i, as a result of a supply shock of animals culled, j, after disease freedom is declared:

$$IC_s = \sum_{j=1}^{3} \sum_{i=1}^{6} (P_{i,d} * Q_{i,d}) - (P_{i,t} * Q_{i,t}) \quad (5)$$

where i denotes commodity markets for beef, pork, lamb, chicken, milk, and feed wheat, and j represents cattle, pig and sheep culled. P_i and Q_i are the price and quantity in the ith commodity market, respectively. t denotes the period before the outbreak and d is the period after disease freedom is declared until the supply shock dissipates. To quantify the total indirect costs across the six markets, the change in revenue is summed across the commodity markets for animals culled for alternative scenarios, S.

$$IC_s = \sum_{j=1}^{3} \sum_{i=1}^{6} (P_{i,t} * (1 + (El_{Pi,j}))) * (Q_{i,t} * (1 + (El_{Qi,j}))) - (P_{i,t} * Q_{i,t}) \quad (6)$$

where $El_{Pi,j}$ is the IRF elasticity of price of the ith market, P_i, with respect to the jth species culled, and the $El_{Qi,j}$ is the IRF elasticity of quantity of the ith market, Q_i, with respect to jth species culled. The IRF elasticities, estimated from the time series model, capture proportional changes in the levels of price and quantity changes as a result of animals culled. Finally, the total economic cost is the sum of indirect and direct costs.

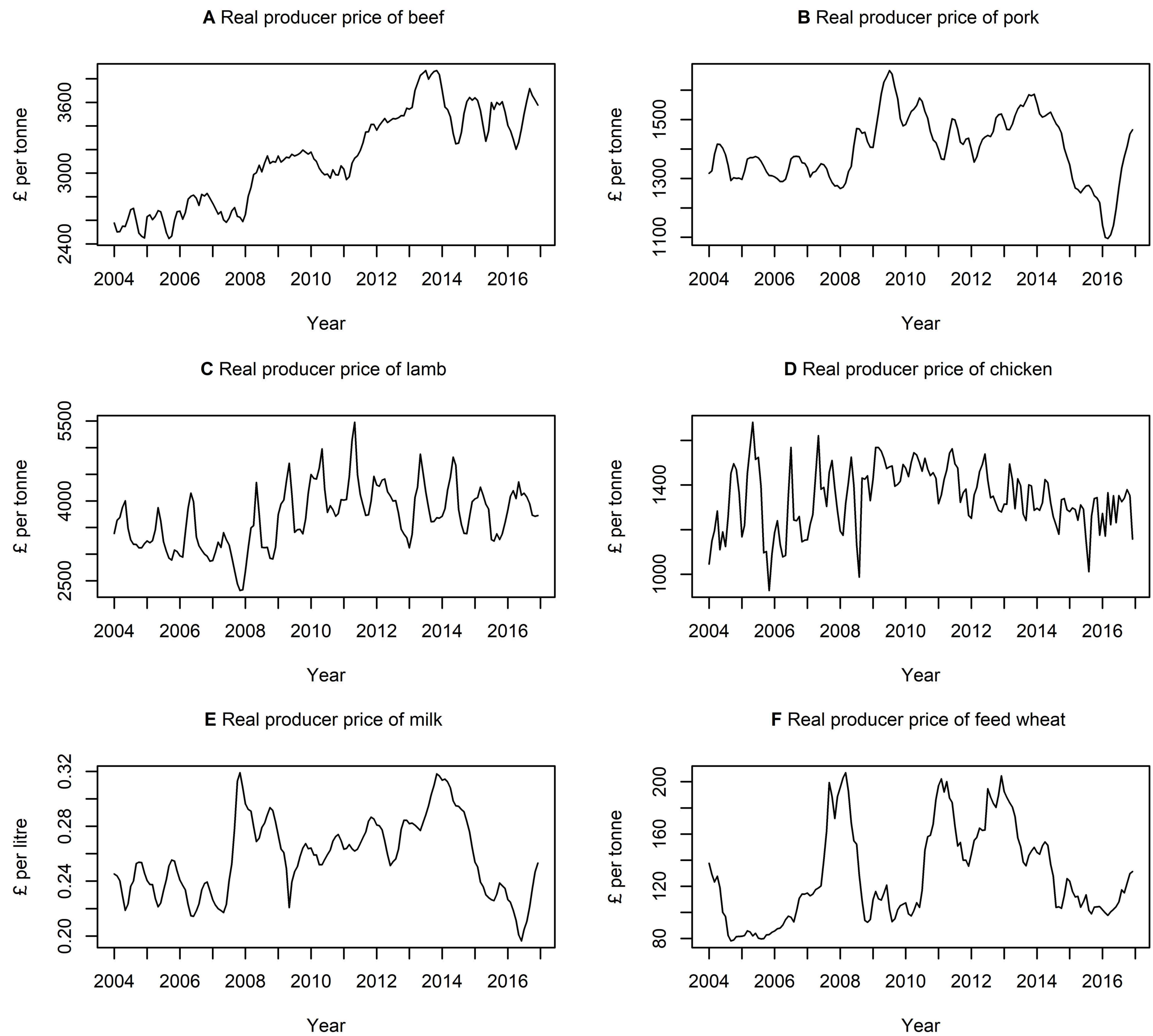

FIGURE 3 | Times series of real producer prices of **(A)** beef, **(B)** pork, **(C)** lamb, **(D)** chicken, **(E)** milk, and **(F)** feed wheat between January 2004 and December 2016, inclusively.

RESULTS

The objective of this paper was to demonstrate a method for estimating the indirect costs, i.e., the economic losses incurred in markets after disease freedom is declared, under alternative disease control strategies using time series analysis.

Data Exploration and Processing

Table 3 presents descriptive statistics for the data series. The lowest and highest variation, according to the coefficient of variation (i.e., ratio of standard deviation to the mean) is quantity of milk produced and quantity of feed wheat produced, respectively. On average, there is a higher variation in the quantity of commodities rather than the price of commodities. **Figures 3**, **4** show the data series of prices and quantities, respectively, plotted over time.

Test of Stationarity and Cointegration

The ADF unit root test (58, 71) was conducted on each data series to determine to what degree data series are integrated. The ADF test indicated that 11 of the 12 data series contained were stationary at $I(1)$), except *QSheep* (i.e., quantity of sheep) which

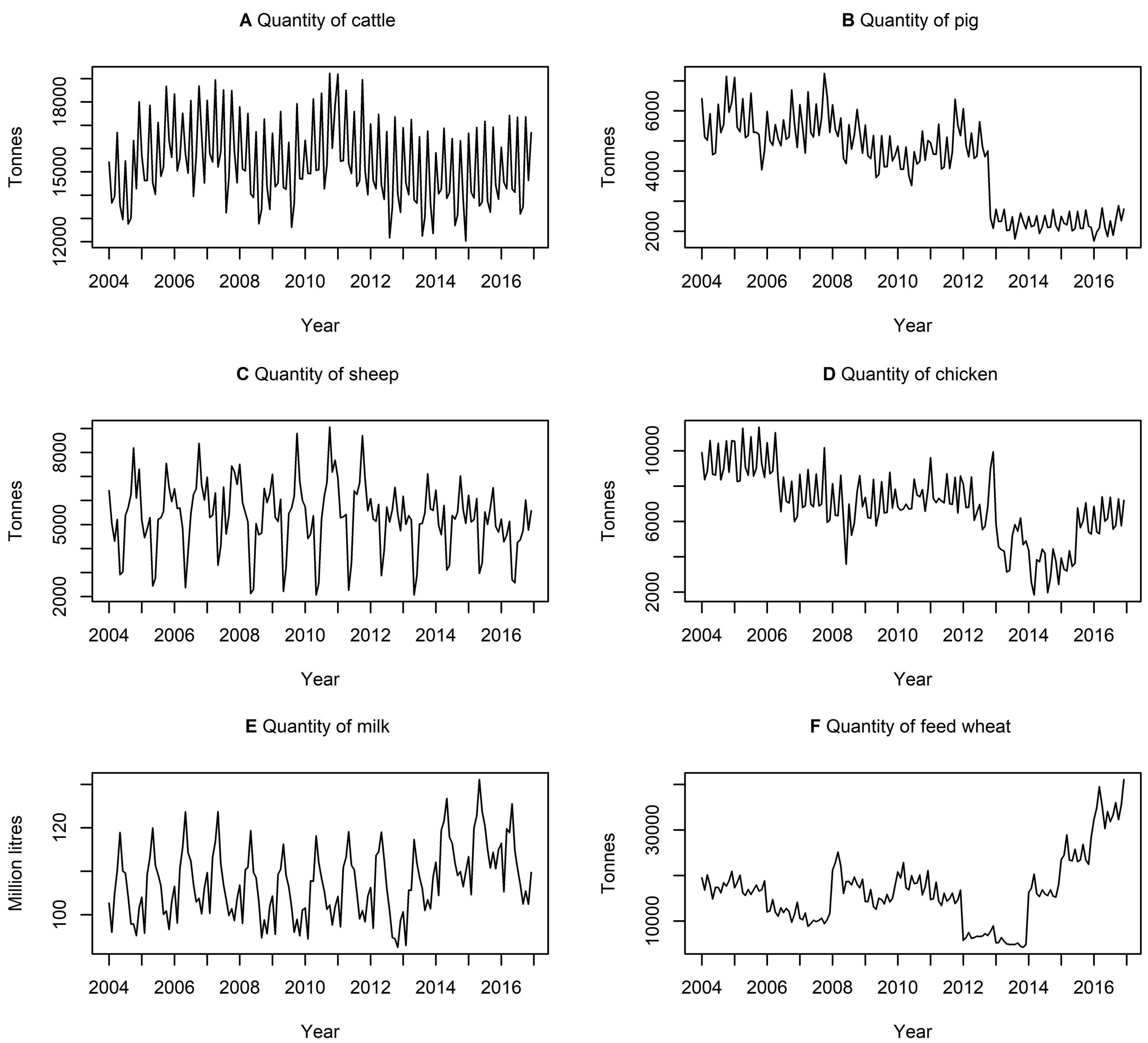

FIGURE 4 | Time series of quantities of **(A)** cattle **(B)** pig **(C)** sheep **(D)** chicken **(E)** milk produced and **(F)** feed wheat produced between January 2004 and December 2016, inclusively.

is stationary at the level, i.e., $I(0)$, at the 5% level of significance. While a VECM requires all variables to be stationary at $I(1)$, in systems with three or more series a VECM is appropriate providing at least two of the variables are stationary at $I(1)$ (72). Therefore, *QSheep* does not impact the validity of our VECM.

The next step was to test for cointegrating relationships between the variables. The Trace statistics (**Table 4**) tests the null hypothesis that there are no cointegrating relationships (i.e., $r = 0$) against the alternative that there is at least one cointegrating relationship (i.e., $r \geq 1$).

The trace statistic (**Table 4**) indicates at least two cointegrating relationships among our data series at the 5% level of significance. Since cointegration is detected, it was incorporated into our model because otherwise its omission contributes to misspecification error.

Vector Error Correction Model

In this paper, a VECM is estimated because of the presence of stationarity in the data series at $I(1)$ and cointegration. Long-run relationships were estimated using maximum likelihood for a VECM(1) with 12 endogenous data series (i.e., $K = 12$), one lag (i.e., $p - 1 = 1$), two cointegrating relationships (i.e., $r = 2$), and a constant deterministic regressor as shown in Allan et al. (7).

TABLE 4 | Johansen cointegration trace test for determining the number of cointegrating relationships, r.

Null hypothesis	Alternative hypothesis	Trace statistic	*p*-value
$r = 0$	$r \geq 1$	373.15	<0.001
$r \leq 1$	$r \geq 2$	292.26	0.02
$r \leq 2$	$r \geq 3$	237.76	0.06
$r \leq 3$	$r \geq 4$	185.55	0.16
$r \leq 4$	$r \geq 5$	141.05	0.32
$r \leq 5$	$r \geq 6$	103.10	0.51
$r \leq 6$	$r \geq 7$	75.88	0.51
$r \leq 7$	$r \geq 8$	54.05	0.46
$r \leq 8$	$r \geq 9$	32.71	0.58
$r \leq 9$	$r \geq 10$	18.65	0.53
$r \leq 10$	$r \geq 11$	8.78	0.39
$r \leq 11$	$r = 12$	3.20	0.07

Maximum-likelihood test of the cointegrating rank.
Trend assumption: Constant.
Lag selection (lag=1) based on Akaike information criterion (AIC) and Bayesian information criterion (BIC).

$$\begin{bmatrix} \Delta In\ PBeef_t \\ \Delta In\ PPork_t \\ In\ PLamb_t \\ \Delta In\ PChicken_t \\ \Delta In\ PMilk_t \\ \Delta In\ PWheat_t \\ \Delta In\ QBeef_t \\ \Delta In\ QPork_t \\ \Delta In\ QSheep_t \\ \Delta In\ QChicken_t \\ \Delta In\ QMilk_t \\ \Delta In\ QWheat_t \end{bmatrix} = \begin{bmatrix} \mu_1 \\ \vdots \\ \mu_{12} \end{bmatrix} + \begin{bmatrix} \Gamma_{1\,1} & \cdots & \Gamma_{1\,12} \\ \vdots & \ddots & \vdots \\ \Gamma_{12\,1} & \cdots & \Gamma_{12\,12} \end{bmatrix} \begin{bmatrix} \Delta In\ PBeef_{t-1} \\ \Delta In\ PPork_{t-1} \\ \Delta In\ PLamb_{t-1} \\ \Delta In\ PChicken_{t-1} \\ \Delta In\ PMilk_{t-1} \\ \Delta In\ PWheat_{t-1} \\ \Delta In\ QBeef_{t-1} \\ \Delta In\ QPork_{t-1} \\ \Delta In\ QSheep_{t-1} \\ \Delta In\ QChicken_{t-1} \\ \Delta In\ QMilk_{t-1} \\ \Delta In\ QWheat_{t-1} \end{bmatrix} + \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \vdots & \vdots \\ \alpha_{12\,1} & \alpha_{12\,2} \end{bmatrix} \begin{bmatrix} \beta_{1\,1} & \dots & \beta_{1\,12} \\ \beta_{2\,1} & \dots & \beta_{2\,12} \end{bmatrix} \begin{bmatrix} In\ PBeef_{t-1} \\ In\ PPork_{t-1} \\ In\ PLamb_{t-1} \\ In\ PChicken_{t-1} \\ In\ PMilk_{t-1} \\ In\ PWheat_{t-1} \\ In\ QBeef_{t-1} \\ In\ QPork_{t-1} \\ In\ QSheep_{t-1} \\ In\ QChicken_{t-1} \\ In\ QMilk_{t-1} \\ In\ QWheat_{t-1} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1\,t} \\ \vdots \\ \varepsilon_{12\,t} \end{bmatrix} \quad (7)$$

The estimated coefficient matrices for the VECM (7) are reported in **Tables S1–S5**.

Impulse Response Function

Once a VECM was identified an impulse response function (IRF) was estimated to evaluate short-run dynamics. The correlation of the variance covariance matrix suggests there is little correlation between the coefficients (**Table S6**). In which case, a generalized IRF is the most appropriate IRF, which is invariant to the order of endogenous variables. A generalized IRF was estimated with 1,000 bootstrapped replications. The supply shocks dissipate in the market variables at different time horizons, from 2 to 13 months. The IRF elasticities capture the response of variables to a 1% shock decrease in the production of cattle (**Figure 5A**), pig (**Figure 5B**), and sheep (**Figure 5C**) due to animals culled until the supply shock dissipates. As described in the Materials and Methods, these IRF elasticities represent a 1% change because the data are expressed in natural logarithms. The IRF elasticities were multiplied by the hypothetical epidemiological shock as a proportion of the national production herd [1,803,937 cattle; 389,995 pigs; and 6,801,134 sheep in June 2011; (70)] to estimate the total impact of the supply shock.

Indirect Costs

The magnitude of indirect, direct, and total costs conducive to large outbreaks is presented in **Figure 6**. These results suggest that economic costs vary with size of the initial vaccine stock. Total economic costs range from £400 to 950 million, with median direct costs between 10 and 24 times larger in magnitude than indirect costs. Indirect costs constitute 9% of total costs under a baseline scenario of no vaccination (i.e., "cull only") and between 4 and 8% of total costs under alternative scenario of "cull plus vaccinate to live" as the size of the initial vaccine bank decreases from 5 to 0.1 million doses. Losses in revenue in some commodity markets (e.g., beef, pork, lamb, and chicken) are partially offset by gains made in other commodity markets (e.g., milk and feed wheat). Hence, the net effect on indirect costs is likely to be lower compared to the presumption that all commodity markets lose revenue during an outbreak.

The distribution of indirect costs, i.e., the economic losses incurred in markets after disease freedom is declared, in the baseline and alternative vaccine stock scenarios is presented in **Figure 7**. Controlling an FMD epidemic with vaccination has a lower median indirect cost than the baseline scenario of no vaccination (i.e., "cull only"). Overall, there is less uncertainty, i.e., spread, in indirect costs associated with vaccination compared to the baseline strategy of no vaccination. Varying the size of the vaccine stock impacts on the variability of indirect costs associated with an outbreak. There is wider variation in indirect costs associated with alternative scenario of between 0.1 and 0.3 million compared to 0.5 to 5 million doses in the vaccine bank. These results suggest that vaccination is relatively more beneficial than a strategy of no vaccination. However, more uncertainty is associated with fewer doses of vaccines (i.e., 0.1 to 0.3 million) compared to more doses of vaccines (i.e., 0.5 to 5 million) in the bank, when considering indirect costs.

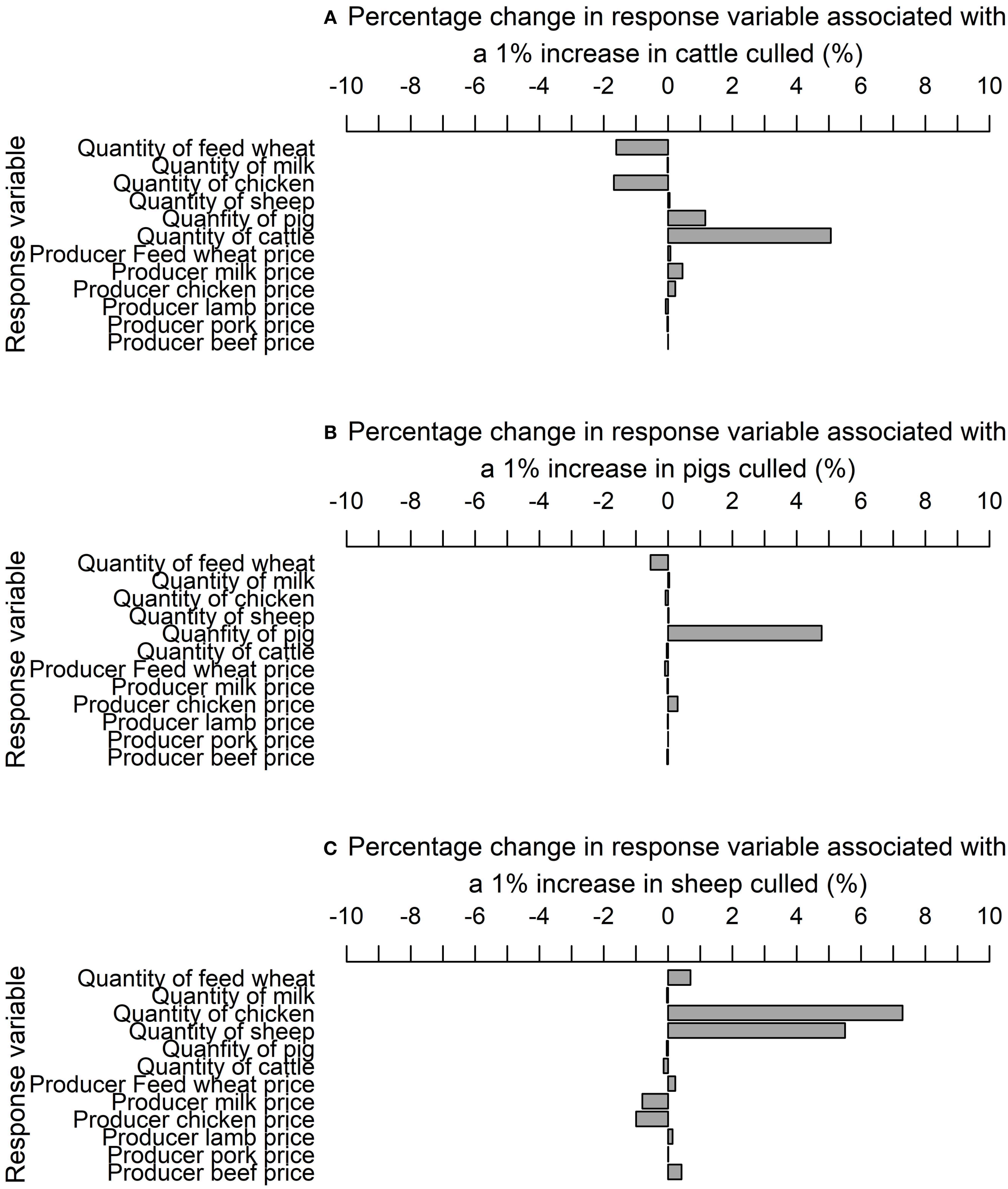

FIGURE 5 | Impulse response elasticities associated with a 1% increase in the quantity of **(A)** cattle **(B)** pig and **(C)** sheep culled for disease control purposes.

DISCUSSION

Our study confirms controlling an FMD epidemic using vaccination costs less, on average, than under a no vaccination strategy (4). In our study, indirect costs constitute only between 4 and 9% of total costs. In other studies indirect costs exceed direct costs, i.e., between 79 and 97% (4) or 29% of total costs (5). Over the last decade the indirect costs of zoonotic disease have contributed 91% of total costs (3). To a certain extent, the ratio of indirect to direct costs may depend on the definition of direct and indirect costs used. Our definition of indirect costs considers indirect costs as the losses after disease freedom is declared and is comprised of change in revenue in various agricultural commodity markets. Economic losses experienced during an outbreak are defined as direct costs. In our study, the loss in revenue in some commodity markets (e.g. beef, pork,

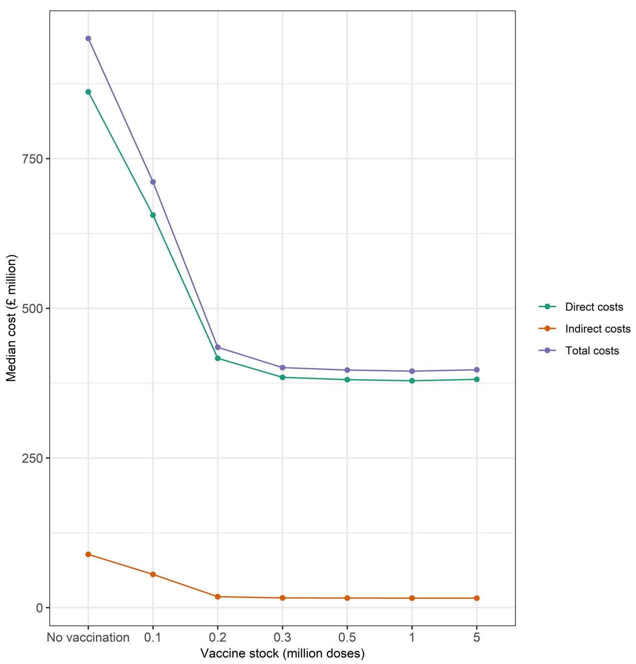

FIGURE 6 | Median direct, indirect, and total costs (£ million) associated with the baseline (no vaccination) and alternative (vaccination) vaccine stock scenarios (i.e., 0.1, 0.2, 0.3, 0.5, 1, and 5 million doses) at the start of the epidemic. Green and orange lines represent median direct and indirect economic costs, respectively.

lamb, and chicken) are partially offset by gains made in other markets (e.g. milk and feed wheat). Therefore, the overall net effect suggests the magnitude of indirect costs is lower than had all the commodity markets suffered a reduction in revenue. Furthermore, the loss in revenue in exports was not considered because export trade data were not available. The loss of export trade may persist beyond disease freedom should importing countries adopt a precautionary approach. Other examples of offsetting could include: decrease in employment in a particular sector and increase in employment to an economy overall; costs to one farm offset by gains to other farms; and reduced tourism expenditure vs. an expansion in household expenditure (7). Furthermore, an exotic disease, such as FMD, is likely to have indirect consequences that were felt over a larger number of sectors than this study attempts to quantify, e.g. tourism, and retail (7). Lower than expected indirect costs may also be explained by the vaccine bank scenarios considered in this paper because only the worst case scenario for direct costs was evaluated (39). In addition, we have not considered the costs of farm management practices such as restocking livestock, following disease freedom, that could have disease implications but such costs could be included as additional component of indirect costs. In the future, it would be interesting to consider other scenarios and how the trade-off between direct and indirect costs varies under alternative prevention and control strategies.

Economic cost frameworks that classify costs as either direct or indirect are often subjective and there lacks a consistent framework to evaluate them, making it difficult to assess the costs of alternative animal disease relative to one another. An economic cost framework should "(1) Be consistent with economic principles; (2) Be derived from and consistent with veterinary control measures; and (3) Include an explicit definition of the economic perspective and the stakeholders included" (18). Our framework meets these three criteria because; (1) it distinguishes objectively between direct and indirect economic costs using disease status to avoid double counting costs; (2) the estimation of costs is derived from veterinary control measures adopted by the Scottish Government in an epidemic scenario; and (3) direct costs incurred during an outbreak are broken down by economic perspective of government and industry (19) while indirect costs come from the economic perspective of markets considered, in our case the producers of agricultural commodities. This indirect cost framework can be extended to other economic perspectives, e.g., tourism and retail, explicitly taking the perspective of stakeholders beyond the farmgate that are impacted after an outbreak, which is often not considered in other studies. This aspect is important for policy makers responsible for disease outbreak prevention and mitigation decisions who may be required to make important and difficult choices at regional, national or international level. Failure to account for impacts beyond the farming sector has been a criticism of decision making in previous UK FMD epidemics (73, 74). Besides the direct costs associated with production, economic models may be called upon to inform producers and policy-makers of the broader knock-on effects associated with indirect costs after disease freedom is declared because such costs might affect various markets and also have implications for trade.

This paper presents a framework that outlines the necessary steps to estimate indirect costs, i.e., the economic losses incurred in markets after disease freedom is declared, using time series analysis. Using agricultural commodity data, time series models can capture market dynamics and the knock-on price and quantity effects between markets, which are often omitted from traditional farm account-based CBAs and other methods. PE and CGE models have been used to explore the indirect costs of animal disease outbreaks. A drawback of these models is that that they are sometimes based on strong assumptions in the absence of good data, e.g., elasticities, defining the demand and supply relationships in multiple sectors to anticipate the likely economic impact of a supply shock. Often elasticities are taken from the literature or assumed unless estimations are developed directly for the model. By contrast, our econometric approach estimates elasticities directly from data to capture production and price dynamics and equilibrium levels, without the need for relying on the literature or making key assumptions and as such can complement PE or CGE models.

PE models can examine a single sector or multiple markets capturing changes in production and prices. An advantage of CGEs over time series models is that they can represent an entire economy. However, a drawback to CGEs is the use of more complex modeling techniques and results that can be difficult to interpret (21). Our time series model can incorporate further markets and sectors, providing such data are available, without

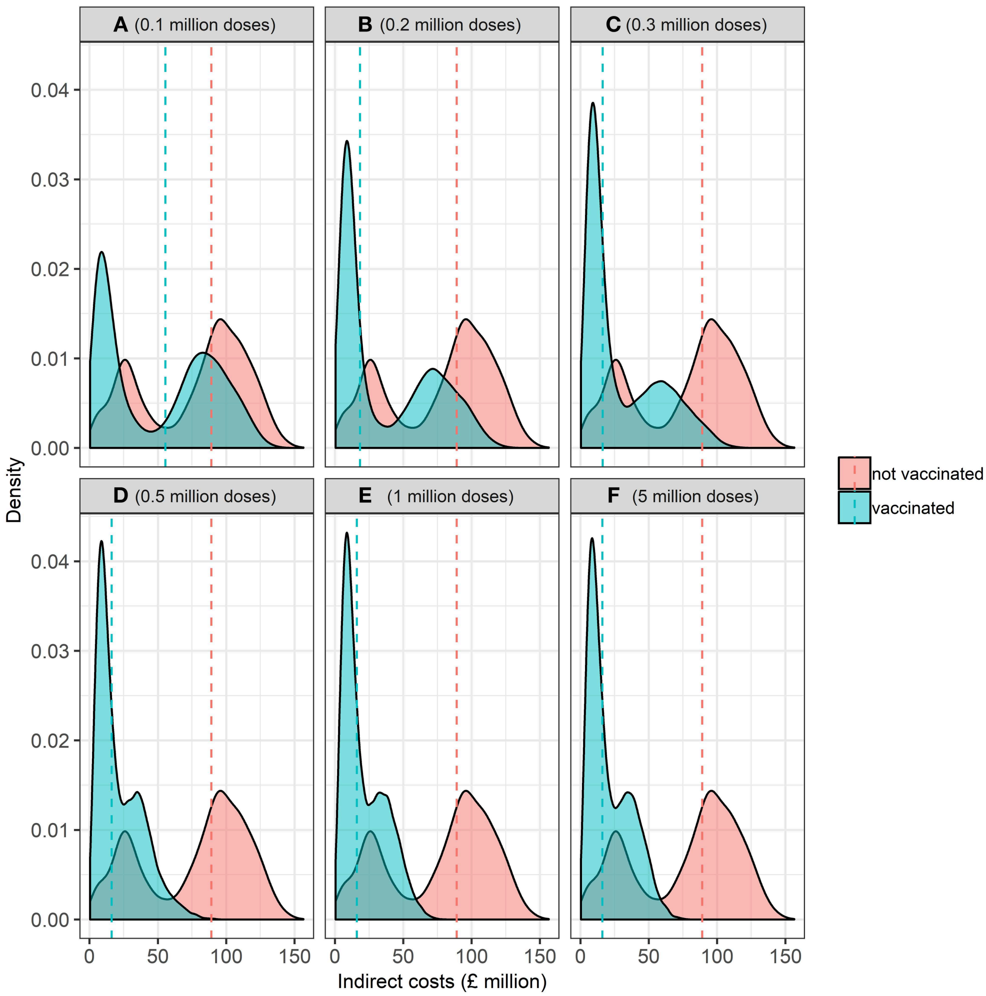

FIGURE 7 | Kernel probability density function of the distribution of indirect economic costs (£ million) associated with the baseline (no vaccination) and alternative (vaccination) vaccine stock scenarios at the start of the epidemic associated with **(A)** 0.1, **(B)** 0.2, **(C)** 0.3, **(D)** 0.5, **(E)** 1, and **(F)** 5 million doses. Dashed vertical red and blue lines represent the median indirect economic costs for the baseline and alternative scenarios, respectively.

the modeling complexity of a CGE. A review of economic models found that CGEs do not explicitly link to an epidemiological model because this requires further development (21). Multi-market models have also been used to model the impact of changing access to export markets on breeding and investment decisions (24). Such integration does not feature in our time series model. Nevertheless, our time series model is linked with the epidemiological model because the indirect costs are derived from the number of animals culled. Although the models are not integrated fully, a development which requires further interdisciplinary research. Despite this, our paper illustrates the usefulness of time series analysis in modeling the indirect economic costs of an animal disease outbreak.

FMD is not a zoonotic disease i.e., it has no human health or food safety risk. For this reason, the retail response of consumer demand was not considered. However, the FMD outbreak of 2001 had psychological impacts on members of the rural community (75). Indirect costs arising from tourism were also not considered. It is suggested that economic losses arising from the tourism industry are similar in magnitude to that of losses to agriculture and the food supply chain (15). Our framework demonstrates how indirect costs can be estimated, but this study does not quantify all potential indirect costs. The scope of indirect costs can be broadened with our methodology provided that appropriate data, such as tourism revenue and retail market, are available. Our IRF was fit with 12 response variables, each with 156 observations (i.e., 13 years of monthly data), and three shocks but did not have enough forecasting power to include additional variables. To investigate the relationship between the supply shock of animals culled and tourism or consumer demand would require an extension of the data series or fewer impulse or response variables, which was not possible for this study. Alternatively, a separate time series model to represent consumer demand and tourism could be considered.

Data availability can also restrict the scope of indirect costs estimated when considering time series modeling. UK market data are available but often such data are not disaggregated into UK administrations, such that regionalization cannot be accurately considered. For this reason, access to publically available data at a disaggregation required, i.e., monthly observations for Scotland, at the farmgate can be problematic. Where possible we have used Scottish-specific data in our model, otherwise UK-level farmgate price and quantity data were adjusted to reflect a regionalisation for Scotland. Likewise, net export trade data were only available quarterly for the UK-level, however such an aggregation did not allow for sufficient variation in the data. Hence, indirect costs do not capture the impact of animal disease outbreak on trade flows. If a country affected by a disease outbreak is a large exporter of livestock, a shock in the domestic market will have knock-on effects into international markets, and consequently international prices if there is an export ban (76).

If animal health is considered a public good (77), better estimates of indirect costs are necessary to support decision-making for animal disease prevention and control strategies.

The Scottish Government's animal health and welfare strategy is to prioritize limited resources and to consider cost sharing responsibilities for preventing and controlling disease. Therefore, indirect costs are a concern for policy makers to understand the cost of alternative prevention and control strategies in context of one another given the allocation of limited resources. Governments need to appropriately balance the costs of disease control between industry and the tax payer, ensuring financial support for farmers and value for money for taxpayers. During the 2001 UK FMD outbreak, farmers were compensated £1.4 billion for the slaughter of animals and disposal and clean-up costs. In addition, the epidemic costed £1.3 billion to eradicate and other public sector costs amounted to £0.3 billion. The private sector was not compensated but also experienced losses; agriculture, food supply chain and supporting services lost £0.6 billion, while the outbreak costed tourism and supporting industries between £4.5–5.4 billion (41). The moral hazard problem arises when not all stakeholders are compensated (78, 79). When compensation is expected it may create incentives for individuals to act in ways that incur costs that they know they will not have to bear. Compensation must be large enough to ensure reporting of disease but not so large to discourage preventative biosecurity (78). Partial compensation helps spread some of the risk responsibility to farmers. Nevertheless, all those that incur losses of an epidemic are not compensated. Therefore, determining how indirect costs are distributed helps address this by informing government of stakeholders, besides farmers and the farming industry, that are impacted by an outbreak and should potentially be considered for compensation after an outbreak is over.

The indirect cost methodology presented in this study is applicable not only to FMD but also other exotic animal diseases. Furthermore, the method is particularly pertinent in light of Brexit, which can be thought of as a "shock" that may alter the UK's livestock disease risk and disrupt markets. It will be important to evaluate the knock-on-indirect effects of alternative Brexit scenarios that are likely to arise from changes to trade rules and access to pharmaceuticals. New trading arrangements may affect the import and export of livestock products and also the movement of animals which may alter the UK's disease risk and interrupt the supply chain. In the context of changing trade relationships with global trading partners under Brexit, understanding indirect costs will become even more important. The UK is a net importer of agri-food production from the EU, which could have implications for EU farming and food sectors (80). The anticipated price and production changes will vary depending on trade agreement considered and whether the UK is a net importer or export of individual commodities concerned (81). There are also concerns as to the supply and access of vaccines post-Brexit (82). In an emergency epidemic, this could pose a risk to the UK's disease status, food security and could have knock-on effects for trade relationships. For example, the UK may no longer have access to the European Union's FMD vaccine bank. The UK has a reference laboratory for FMD but in the face of an outbreak would the UK's national vaccine bank have sufficient stock? Hence, as much uncertainty remains, it is important that alternative Brexit scenarios are considered to anticipate the perceived impact of leaving the EU on various agricultural markets and rural sectors of the economy and the implications for disease risk and the associated economic costs.

CONCLUSION

In conclusion, this paper has presented a framework for defining and estimating the indirect costs, i.e., the economic losses incurred in markets after disease freedom is declared, of an animal disease outbreak. The time series model identified was a VECM, a useful tool for capturing knock-on market dynamics following a disease freedom/outbreak. Overall, in terms of indirect costs it is more beneficial to vaccinate compared to a "cull only" FMD control strategy. Our findings suggest indirect costs vary with the size of the initial vaccine stock and are less variable when vaccination is used instead of culling. The estimation of indirect costs contributes to the overall economic assessment of the costs of an animal disease outbreak, which is often overlooked but is necessary in support of decision-making. In future, constraints on data and analytical frameworks that otherwise limit the estimation of indirect costs should be addressed. The framework presented can be applied to other animal disease scenarios to more consistently evaluate indirect costs. It is important that indirect costs are not overlooked because their estimation is necessary for a more complete picture of the costs of animal disease outbreaks across case studies to better prioritize limited resources and inform cost sharing. Our indirect cost modeling framework can be adapted to model how changes in the political economy, such as Brexit, might impact the cost of animal disease outbreaks in the future.

AUTHOR CONTRIBUTIONS

AS developed the initial concept with GG, Dr. Habtu Weldegebriel, and TP, with further refinement from AB and KR. AB gathered data, developed the indirect cost model with KR and JE and carried out the modeling. AB drafted the paper, and KR, JE, AS, TP, and GG also contributed to the manuscript. GG and AS secured funding and led the project. All authors gave final approval for publication.

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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.2019.00190/full#supplementary-material

REFERENCES

1. Dehove A, Commault J, Petitclerc M, Teissier M, Macé J. Economic analysis and costing of animal health: a literature review of methods and importance. *Rev Off Int Epizoot.* (2012) 31:605–17. doi: 10.20506/rst.31.2.2146
2. FAO. *The Economic Losses Caused by Animal Disease*. Food and Agriculture Organization of the United Nations, Rome (1962). Available online at: http://www.fao.org/3/a-i5512e.pdf
3. World Bank. *People, Pathogens and Our Planet, volume 1: Towards a One Health Approach for Controlling Zoonotic Diseases* (2010).
4. Berentsen P, Dijkhuizen A, Oskam A. A dynamic model for cost-benefit analyses of foot-and-mouth disease control strategies. *Prev Vet Med.* (1992) 12:229–43. doi: 10.1016/0167-5877(92)90052-H
5. Fofana A, Toma L, Moran D, Gunn G, Gubbins S, Szmaragd C, et al. An ex-ante economic appraisal of Bluetongue virus incursions and control strategies. *J Agric Sci.* (2016) 154:118–35. doi: 10.1017/S0021859615000015
6. Dijkhuizen AA, Morris RS. *Animal Health Economics*: *Principles and Applications.* University of Sydney, Post-Graduate Foundation in Veterinary Science (1997).
7. Allan G, McLellan D, Swales J. *The Economic Impact of the 2001 Foot and Mouth Disease Outbreak in Scotland*. Working paper, University of Strathclyde (2003).
8. Knight-Jones T, Rushton J. The economic impacts of foot and mouth disease–What are they, how big are they and where do they occur? *Prev Vet Med.* (2013) 112:161–73. doi: 10.1016/j.prevetmed.2013.07.013
9. McInerney J, Howe K, Schepers J. A framework for the economic analysis of disease in farm livestock. *Prev Vet Med.* (1992) 13:137–54. doi: 10.1016/0167-5877(92)90098-Z
10. Bennett R. The 'direct costs' of livestock disease: the development of a system of models for the analysis of 30 endemic livestock diseases in Great Britain. *J Agric Econ.* (2003) 54:55–71. doi: 10.1111/j.1477-9552.2003.tb00048.x
11. Rushton J, Thornton PK, Otte MJ. Methods of economic impact assessment. *Rev Sci Tech.* (1999) 18:315–42. doi: 10.20506/rst.18.2.1172
12. Boklund A, Halasa T, Christiansen LE, Enøe C. Comparing control strategies against foot-and-mouth disease: will vaccination be cost-effective in Denmark? *Prev Vet Med.* (2013) 111:206–19. doi: 10.1016/j.prevetmed.2013.05.008
13. Ivanova P, Ivanova E. Economic model for calculation of direct and indirect economical losses from African swine fever occurrence. *Bulg J Vet Med.* (2017) 2017:1–10. doi: 10.15547/bjvm.2037
14. Gethmann J, Probst C, Sauter-Louis C, Conraths FJ. Economic analysis of animal disease outbreaks - BSE and Bluetongue disease as examples. *Berl Munch Tierarztl Wochenschr.* (2015) 128:478–82. doi: 10.2376/0005-9366-128-478
15. Thompson D, Muriel P, Russell D, Osborne P, Bromley A, Rowland M, et al. Economic costs of the foot and mouth disease outbreak in the United Kingdom in 2001. *Rev Sci Tech.* (2002) 21:675–85. doi: 10.20506/rst.21.3.1353
16. Carpenter TE, O'Brien JM, Hagerman AD, McCarl BA. Epidemic and economic impacts of delayed detection of foot-and-mouth disease: a case study of a simulated outbreak in California. *J Vet Diagn Invest.* (2011) 23:26–33. doi: 10.1177/104063871102300104
17. Kompas T, Nguyen HTM, Van Ha P. Food and biosecurity: livestock production and towards a world free of foot-and-mouth disease. *Food Secur.* (2015) 7:291–302. doi: 10.1007/s12571-015-0436-y
18. Saatkamp H, Mourits M, Howe K. A framework for categorization of the economic impacts of outbreaks of highly contagious livestock diseases. *Transbound Emerg Dis.* (2016) 63:422–34. doi: 10.1111/tbed.12286
19. Porphyre T, Rich KM, Auty HK. Assessing the economic impact of vaccine availability when controlling foot and mouth disease outbreaks. *Front Vet Sci.* (2018) 5:47. doi: 10.3389/fvets.2018.00047
20. Rich K, Miller G, Winter-Nelson A. A review of economic tools for the assessment of animal disease outbreaks. *Rev Sci Tech.* (2005) 24:833. doi: 10.20506/rst.24.3.1618
21. Rich KM, Winter-Nelson A, Miller GY. Enhancing economic models for the analysis of animal disease. *Rev Sci Tech.* (2005) 24:847–56. doi: 10.20506/rst.24.3.1617
22. Paarlberg PL, Lee JG, Seitzinger AH. Potential revenue impact of an outbreak of foot-and-mouth disease in the United States. *J Am Vet Med Assoc.* (2002) 220:988–92. doi: 10.2460/javma.2002.220.988
23. Mangen M, Burrell A. Who gains, who loses? Welfare effects of classical swine fever epidemics in the Netherlands. *Eur Rev Agric Econ.* (2003) 30:125–54. doi: 10.1093/erae/30.2.125
24. Rich KM, Winter-Nelson A. An integrated epidemiological-economic analysis of foot and mouth disease: applications to the southern cone of South America. *Am J Agric Econ.* (2007) 89:682–97. doi: 10.1111/j.1467-8276.2007.01006.x
25. Perry B, Randolph T, Ashley S, Chimedza R, Forman T, Morrison J, et al. *The Impact and Poverty Reduction Implications of Foot and Mouth Disease Control in Southern Africa With Special Reference to Zimbabwe*. International Livestock Research Institute (ILRI), Nairobi (2003).
26. O'Toole R, Matthews A, Mulvey M. *Impact of the 2001 Foot and Mouth Outbreak on the Irish Economy*. Ireland: Department of Economics, Trinity College Dublin (2002).
27. Harvey AC. *The Econometric Analysis of Time Series*. Cambridge, MA: MIT Press (1990).
28. Park M, Jin YH, Bessler DA. The impacts of animal disease crises on the Korean meat market. *Agric Econ.* (2008) 39:183–95. doi: 10.1111/j.1574-0862.2008.00325.x
29. Abao LNB, Kono H, Gunarathne A, Promentilla RR, Gaerlan MZ. Impact of foot-and-mouth disease on pork and chicken prices in Central Luzon, Philippines. *Prev Vet Med.* (2014) 113:398–406. doi: 10.1016/j.prevetmed.2013.12.005
30. Lütkepohl H. *New Introduction to Multiple Time Series Analysis*. Berlin: Springer Science & Business Media (2005). doi: 10.1007/978-3-540-27752-1

31. Sargent TJ, Sims CA. Business cycle modeling without pretending to have too much a priori economic theory. In: *New Methods In Business Cycle Research*. Vol. 1. Minneapolis, MN (1977). p. 145–68.
32. Pesaran MH, Shin, Y. An autoregressive distributed-lag modelling approach to cointegration analysis. *Econom Soc Monogr.* (1998) 31:371–413. doi: 10.1017/CCOL521633230.011
33. Johansen S. Estimation and hypothesis testing of cointegration vectors in Gaussian vector autoregressive models. *Econometrica.* (1991) 1991:1551–80. doi: 10.2307/2938278
34. Pesaran HH, Shin Y. Generalized impulse response analysis in linear multivariate models. *Econ Lett.* (1998) 58:17–29. doi: 10.1016/S0165-1765(97)00214-0
35. Borovička J, Hansen LP, Scheinkman JA. Shock elasticities and impulse responses. *Math Financ Eco.* (2014) 8:333–54. doi: 10.1007/s11579-014-0122-4
36. FAO. *Economic analysis of animal diseases. Food and Agriculture Organization of the United Nations*, Rome (2016). Available online at: http://www.fao.org/3/a-i5512e.pdf
37. Webby RJ, Webster RG. Are we ready for pandemic influenza? *Science.* (2003) 302:1519–22. doi: 10.1126/science.1090350
38. Peiris JM, De Jong MD, Guan Y. Avian influenza virus (H5N1): a threat to human health. *Clin Microbiol Rev.* (2007) 20:243–67. doi: 10.1128/CMR.00037-06
39. Porphyre T, Auty HK, Tildesley MJ, Gunn GJ, Woolhouse ME. Vaccination against foot-and-mouth disease: do initial conditions affect its benefit? *PLoS ONE.* (2013) 8:e77616. doi: 10.1371/journal.pone.0077616
40. Anderson I. *Foot and Mouth Disease 2007*: *A Review and Lessons Learned*. The Stationery Office (2008).
41. National Audit Office. *The 2001 Outbreak of Foot and Mouth Disease*. Report by the Comptroller and Auditor General HC 939 Session 2001-2002 (2002).
42. Scottish Government. "*Scottish Government's Exotic Animal Disease Contingency Framework Plan - Annex 4 Foot and Mouth disease*." (2010). Available online at: https://www.gov.scot/Resource/Doc/299205/0093308.pdf (accessed July/30:2018)
43. AHDB. "*UK, GB and NI Farmgate Milk Prices.*" (2017). Available online at: https://dairy.ahdb.org.uk/resources-library/market-information/milk-prices-contracts/uk-farmgate-milk-prices/#.W2A9lPZFyM9 (accessed August 28:2017)
44. AHDB. "*Market Data Centre: Physcial Prices.*" (2017). Available online at: https://cereals-data.ahdb.org.uk/demand/physical.asp (accessed August/21:2017)
45. AHDB. "*UK Monthly and Annual Milk Deliveries.*" (2017). Available online at: https://dairy.ahdb.org.uk/market-information/supply-production/milk-production/uk-monthly-and-annual-milk-deliveries/#.W2BrB_ZFyM8 (accessed August/18:2017)
46. Defra. "*Monthly Statistics on Raw Material Usage and Production of Compund Animal Feed by Manufacturers in Great Britain.*"(2017). Available online at: https://www.gov.uk/government/statistics/animal-feed-production (accessed August/24:2017)
47. ONS. "*Producer Price Inflation Time Series (JNZ7).*" (2018). Available online at: https://www.ons.gov.uk/economy/inflationandpriceindices/timeseries/jvz7/ppi?referrer=search&searchTerm=jvz7 (accessed April/16:2018)
48. ONS. *UK Relative Regional Consumer Price Levels for Goods and Services for 2010*. Newport (2011). Available online at: http://webarchive.nationalarchives.gov.uk/20151014001900/http://www.ons.gov.uk/ons/rel/cpi/regional-consumer-price-levels/2010/index.html
49. Milk Clarity. "*UK Production, its Decline and the Influence of Government Policy*." (2016). Available online at: http://milk.withclarity.co.uk/ (accessed August/21:2017)
50. Scottish Government. "*Economic Report on Scottish Agriculture: 2017 edition - Charts and Associated Data. (Table A3: Output and Utilisation of Cereals and Oilseed Rape, 2003 to 2016.*" (2017). Available online at: https://www.gov.scot/Topics/Statistics/Browse/Agriculture-Fisheries/PubEconomicReport/2017docs (accessed August/24:2017)
51. Scottish Executive. *Scottish Primary Food and Drink Produce Processed in Scotland*, Edinburgh (2007).. Available online at: https://www.gov.scot/Resource/Doc/196509/0052657.pdf
52. Wooldridge JM. *Introductory Econometrics*: *A Modern Approach*. Mason, IA: Thomson South-Western (2006).
53. Johnston J, DiNardo J. *Econometric Methods*. Asia: McGraw-Hill International Editions (2007).
54. Diebold FX. Discussion: the effect of seasonal adjustment filters on tests for a unit root. *J. Econ.* (1993) 55:99–103.
55. Ghysels E, Perron P. The effect of seasonal adjustment filters on tests for a unit root. *J Econ.* (1993) 55:57–98. doi: 10.1016/0304-4076(93)90004-O
56. Bell WR. Unit root properties of seasonal adjustment and related filters. *J Official Stat.* (2012) 28:441. doi: 10.1515/jos-2017-0001
57. del Barrio Castro T, Osborn DR. The consequences of seasonal adjustment for periodic autoregressive processes. *Econometr J.* (2004) 7:307–21. doi: 10.1111/j.1368-423X.2004.00132.x
58. Dickey DA, Fuller WA. Distribution of the estimators for autoregressive time series with a unit root. *J Am Stat Assoc.* (1979) 74:427–31. doi: 10.1080/01621459.1979.10482531
59. Wang D, Tomek WG. Commodity prices and unit root tests. *Am J Agric Econ.* (2007) 89:873–89. doi: 10.1111/j.1467-8276.2007.01031.x
60. Granger CW. Investigating causal relations by econometric models and cross-spectral methods. *Econometrica.* (1969) 1969:424–38. doi: 10.2307/1912791
61. Granger CW. Some properties of time series data and their use in econometric model specification. *J Econ.* (1981) 16:121–30. doi: 10.1016/0304-4076(81)90079-8
62. Engle RF, Granger CW. Co-integration and error correction: representation, estimation, and testing. *Econometrica.* (1987) 1987:251–76. doi: 10.2307/1913236
63. Keeling MJ, Woolhouse ME, Shaw DJ, Matthews L, Chase-Topping M, Haydon DT, et al. Dynamics of the 2001 UK foot and mouth epidemic: stochastic dispersal in a heterogeneous landscape. *Science.* (2001) 294:813–7. doi: 10.1126/science.1065973
64. Keeling M, Woolhouse M, May R, Davies G, Grenfell B. Modelling vaccination strategies against foot-and-mouth disease. *Nature.* (2003) 421:136. doi: 10.1038/nature01343
65. Tildesley MJ, Savill NJ, Shaw DJ, Deardon R, Brooks SP, Woolhouse ME, et al. Optimal reactive vaccination strategies for a foot-and-mouth outbreak in the UK. *Nature.* (2006) 440:83. doi: 10.1038/nature04324
66. Tildesley MJ, Bessell PR, Keeling MJ, Woolhouse ME. The role of pre-emptive culling in the control of foot-and-mouth disease. *Proc R Soc Lond B Biol Sci.* (2009) 276:3239–48. doi: 10.1098/rspb.2009.0427
67. Tildesley MJ, House TA, Bruhn MC, Curry RJ, O'Neil M, Allpress JL, et al. Impact of spatial clustering on disease transmission and optimal control. *Proc Natl Acad Sci USA.* (2010) 107:1041–6. doi: 10.1073/pnas.0909047107
68. Gibbens JC, Sharpe CE, Wilesmith JW, Mansley LM, Michalopoulou E, Ryan JB, et al. Descriptive epidemiology of the 2001 foot-and-mouth disease epidemic in Great Britain: the first five months. *Vet Rec.* (2001) 149:729–43. doi: 10.1136/vr.149.24.729
69. Green D, Kiss I, Kao R. Modelling the initial spread of foot-and-mouth disease through animal movements. *Proc R Soc B Biol Sci.* (2006) 273:2729–35. doi: 10.1098/rspb.2006.3648
70. Scottish Government. *Results From the 2011 June Agricultural Census.* (2011). Available online at: https://www.gov.scot/Resource/Doc/358779/0121281.pdf
71. Dickey DA, Fuller WA. Likelihood ratio statistics for autoregressive time series with a unit root. *Econometrica.* (1981) 1981:1057–72. doi: 10.2307/1912517
72. Banerjee A, Lumsdaine RL, Stock JH. Recursive and sequential tests of the unit-root and trend-break hypotheses: theory and international evidence. *J Bus Econ Stat.* (1992) 10:271–87. doi: 10.1080/07350015.1992.10509905
73. Ward N, Donaldson A, Lowe P. Policy framing and learning the lessons from the UK's foot and mouth disease crisis. *Environ Plann C Gov Policy.* (2004) 22:291–306. doi: 10.1068/c0209s
74. Taylor I. Policy on the hoof: the handling of the foot and mouth disease outbreak in the UK 2001. *Policy Pol.* (2003) 31:535–46. doi: 10.1332/030557303322439399

75. Hall MJ, Ng A, Ursano RJ, Holloway H, Fullerton C, Casper J. Psychological impact of the animal-human bond in disaster preparedness and response. *J Psychiatr Pract.* (2004) 10:368–74. doi: 10.1097/00131746-200411000-00005
76. Junker F, Ilicic-Komorowska J, Van Tongeren F. Imipact of animal disease outbreaks and alternative control practices on agricultural markets and trade. In: *OECD Food Agriculture and Fisheries Working Papers, No*. 19 (2009).
77. WHO-OIE. *Operational Framework for Good Governance at the Human-Animal Interface: Bridging WHO and OIE Tools for the Assessment of National Capacities*. Geneva (2014). Available online at: https://www.who.int/ihr/publications/WHO-OIE_Operational_Framework.pdf?ua=1
78. Hennessy DA, Wolf CA. Asymmetric information, externalities and incentives in animal disease prevention and control. *J Agric Econ.* (2018) 69:226–42. doi: 10.1111/1477-9552.12113
79. Gramig BM, Horan RD, Wolf CA. Livestock disease indemnity design when moral hazard is followed by adverse selection. *Am J Agric Econ.* (2009) 91:627–41. doi: 10.1111/j.1467-8276.2009.01256.x
80. Matthews A. The Potential Implications of a Brexit for Future EU Agri-food Policies. *EuroChoices.* (2016) 15:17–23. doi: 10.1111/1746-692X.12128
81. Davis J, Feng S, Patton M, Binfield J. *Impacts of Alternative Post-Brexit Trade Agreements on UK Agriculture: Sector Analyses Using the FAPRI-UK Model.* FAPRI-UK Project, Agri-Food and Biosciences Institute and University of Missouri (2017).
82. Loeb J. Concerns about the supply of medicines post-Brexit. *Vet Rec.* (2018) 182:650. doi: 10.1136/vr.k2519

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Control of *Taenia solium*; A Case for Public and Private Sector Investment

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The zoonotic helminth *T. solium* is one of the leading causes of acquired epilepsy in endemic countries, resulting in a high burden both in human health and social stigma of affected people (1–3). In 2012 *T. solium* was highlighted as a priority for control in the World Health Assembly resolution 66.12 (4). Despite a call for validated control strategies by 2015 and a "Tool Kit" of control options being available, relatively few examples of successfully implemented and sustainable control programs are available (5–7). A minimal control strategy focusing solely on the porcine host has also been proposed although the cost-effectiveness of such has yet to be explored (8). Although acknowledgment has been made of the need for initiatives to be sustainable, we are yet to see sufficient consideration of the balance between the provision of public and private goods, and the need for engagement of the people and organizations in the pork value chains within *T. solium* control strategies. We utilized a food chain risk analysis model to determine the incremental cost-effectiveness ratio (ICER) in terms of $/infective meal avoided, of combining a pharmaceutical intervention in pigs with strengthened meat hygiene services. The addition of a vaccination and treatment protocol, at an additional 10.3% cost, was illustrated to have the potential to improve the ICER of improving meat inspection by 74.6%. The vaccination and treatment protocol also had the potential to reduce the losses borne by the pork industry of condemned meat by 66%, highlighting the potential to leverage private sector investment in *T. solium* control.

Keywords: ***Taenia solium*, cysticercosis, control, interventions, economics, incentives**

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INTRODUCTION

Taenia solium is a zoonotic tapeworm which utilizes a porcine intermediate and a human definitive host. It is thought that *T. solium* has been associated with a hominid definitive host pre-dating the advent of *Homo sapiens* (9) and has accompanied modern humans as they colonized the globe (10). Humans acquire a *T. solium* taeniosis infection through consumption of pork containing viable cysticerci and pigs acquire *T. solium* cysticercosis through the ingestion of infective eggs or proglottids excreted in the feces of infected humans (11). The ingestion of infective eggs by humans due to fecal contamination of food or drinking water, or auto-infection from a tapeworm carrier, can lead to an aberrant intermediate infection, cysticercosis, with larval cysts found in muscle, optical or neural tissue. Infection of the central nervous tissue, neurocysticercosis (NCC) is considered to be a major causes of acquired epilepsy in endemic counties (12), leading to significant reductions in quality of life (13) and making *T. solium* the foodborne parasite with the greatest global burden (14).

Improvements in pig production, sanitation and meat hygiene have contributed to the decline in *T. solium* infection pressure in North America and Europe, although pockets of endemnicity exist where a triad of poor sanitation, free-range pigs and lack of food safety governance are found, making it very much a disease of poverty (15). The three major endemic regions are Africa, Asia, and Latin America (16), although there is evidence that the parasite may still have autochthonous transmission within Eastern Europe (17). Even within individual countries in endemic regions the parasite has a varied spatial and temporal distribution depending on local factors influencing the lifecycle (18).

T. solium taeniosis/cysticercosis has traditionally been considered one of the neglected zoonotic diseases (19–22) but increased advocacy and a growing body of literature detailing the prevalence and burden of this parasite has led to its incorporation into the 2012 London Declaration on Neglected Topical Diseases (NTDs) (23), The WHO Roadmap "Accelerating work to overcome the global impact of neglected tropical diseases" (24) and the World Health Assembly resolution WHA66.12 (25).

Despite this high-level commitment we have yet to significantly advance the control of the parasite on a large scale. As a community, we have failed to achieve the 2015 goal set by the WHO Roadmap, to have a "validated strategy for control and elimination of *T. solium* taeniosis/cysticercosis available" and are unlikely to meet the 2020 goal for scaled up interventions. A "tool kit" of intervention options are available, each of which has the potential to break the tapeworm lifecycle at different points by focusing on either the human or porcine host (7).

Interventions targeting the human host include improving access to clean water and sanitation, preventative chemotherapy (often in the form of mass drug administration) and wider public health education campaigns (26). Control interventions in the porcine host and associated value chain such as the confinement, anthelmintic treatment or vaccination of pigs can be considered as pre-harvest (26). Post-harvest control covers stringent meat inspection with condemnation of infected meat (27), treatment of meat through freezing (28), gamma-radiation (29), and salt-pickling (30) as well as cooking to over 50°C (30, 31) which also assists in the control of other foodborne pathogens (32–34).

An optimal intervention strategy has not yet been demonstrated in the field and importantly the acceptability and sustainability of these strategies has not been evaluated (6, 35–37), with the cost-effectiveness of control evaluated in only two studies to date (38, 39). A "One Health" approach, with interventions in both the human and non-human animal host has generally been regarded to be necessary for the control of zoonoses such as *T. solium* (40). It has recently been suggested that a "minimal intervention strategy" targeting only the porcine host through vaccination and anthelmintic treatment of pigs between 2 and 7 months of age may be appropriate (8).

The One Health strategy utilizes the TSOL18 vaccine which has demonstrated 100% protection against porcine cysticercosis under field conditions (41) and which is now produced by India Immunologicals Ltd, India as Cysvax® (8). The anthelmintic treatment to be administered is oxfendazole, administered at 30 mg/kg, now available in some African countries as a 10% formulation for pigs (Paranthic) (8). Oxfendazole (30 mg/kg) has also been demonstrated to also have 100% efficacy against the gastrointestinal nematodes *Ascaris suum, Oesophagostomum* spp., *Trichuris suis* and *Metastrongylus* spp., thereby providing additional benefits to productivity for pig farmers (42). A recent trial of this strategy in Nepal demonstrated a significant reduction in porcine cysticercosis, with elimination of infection in those animals assessed by post-mortem (43).

In an integrated control program in Laos PDR, a pig intervention including the TSOL18 vaccine, oxfendazole (30 mg/kg), was combined with *T. solium* and soil transmitted helminth control in humans through the mass administration of Albendazole (44). An economic analysis of this program from a societal perspective has been conducted and the combined approach was judged to be highly cost-effective at 214 USD/DALY averted against the GDP per capita of Laos PDR of 1,793 USD (38).

As yet all studies utilizing porcine pharmaceutical interventions have been provided to farmers free of charge. Whilst acknowledging the barriers, including lack of access to finance or credit to make capital investments of feed purchases (45), to improve the pork value chain in endemic areas, it is important to provide value chain actors with the responsibility and agency to deliver a safe and quality product to market, if sustainable control is to be achieved. We suggest that a cost-sharing model between the private and public sector may be a suitable direction to take for *T. solium* control, based upon the delivery of private (e.g., profit) or public (e.g., food safety) goods through the different control interventions.

We hypothesize that farmers may be incentivized to adopt a control strategy through demonstration of "rewards," such as increased profitability of the pig production system due to improved husbandry practices or the adoption of judicial use of anthelmintic treatment for gastro-intestinal nematode infections in combination with *T. solium* control. Behavior change may also be encouraged through potential punishments, such as the condemnation of grossly infected meat at inspection.

Despite the low sensitivity of meat inspection for the detection of *T. solium* (46), highly infected carcasses are likely to be observed if qualified personnel are present at slaughter, well trained and sensitized to the importance of preventing consumption of infected meat. If meat inspection is carried out according to regulatory standards, a trader or butcher who presents a pig to slaughter carries the full burden of risk should that carcass be condemned at meat inspection as no compensation is received for condemned animals (47).

Changes in demand, toward uninfected pigs, may induce losses for small-holder pig farmers until they adopt *T. solium* control strategies. It could be hypothesized therefore, that the public expenditure of enforcing meat hygiene regulations may therefore "leverage" investment from the private sector in control measures (48). An example of such would be the purchase of vaccines and anthelmintic treatment for pigs directly by farmers, rather than through publicly funded campaigns.

The current study aimed to explore this hypothesis by determining the incremental cost-effectiveness ratio (ICER) in terms of $/infective meal avoided, of the "minimal intervention strategy" of pharmaceutical intervention in pigs in combination with strengthened meat hygiene services in western Kenya. We utilize a food chain risk analysis modified from Thomas et al. (49) parameterized by data relating to western Kenya although the model parameters may be easily adjusted for use in other settings.

MATERIALS AND METHODS

Study Area

The data used to parameterize the risk model described below was obtained through previously described studies conducted in a mixed crop-livestock farming community in western Kenya, centered around Busia town on the Uganda border (50, 51). Many pig farmers in this area practice extensive forms of pig production, with three systems predominating; full time free range where pigs are left to scavenge for all their food requirements, part-time free-range where pigs scavenge during the dry season, where during planting or growing seasons they may be tethered or confined with supplemental feedstuffs to prevent crop damage, or full time confined systems which may involve tethering or confining pigs in rudimentary structures and providing supplementary feedstuffs (52–54). These systems are similar to those described in other endemic areas (55–60). Within the study site, 16.6% (95% C.I. 13.1–20.5) of homesteads owned pigs, and the majority of farmers sell their pigs to butchers who transport the pigs to rudimentary, but licensed, slaughter premises for slaughter, with a small, but important proportion (4.3%, 95% C.I 2–12%) of pigs undergoing "back-yard" slaughter (52). By law, a meat inspector must inspect each pig, although low staffing levels and poor facilitation in terms of transport, means that many animals are currently slaughtered without inspection.

Food Chain Risk Analysis

A stochastic risk assessment model, built using the @Risk (Palisade, Newfield, NY, USA) add-on for Excel (Microsoft corp., USA) and the initial parameters (P1–P25) are described in detail in Thomas et al. (49). The structure of the model is illustrated in **Figure 1** for ease of reference. This model indicates that any one pork meal consumed in western Kenya has a 0.006 (99% Uncertainty Interval (U.I). 0.0002 ± 0.0164) probability of containing at least one viable *T. solium* cysticercus at the point of consumption and therefore being potentially infectious to humans (49). We adapted this model to investigate the ICER from a societal perspective of enforcing best practice meat inspection at every registered porcine slaughter facility in Busia county with or without adoption of a regime of Cysvax vaccine and Oxfendazole in pigs at 3 and 6 months of age, adapted from the minimal intervention strategy as recommended by Lightowlers and Donadeu (8).

The assumptions in this adapted model are as follows:

- Pigs are slaughtered between 7 and 12 months of age
- Adoption of vaccination and treatment protocol was assumed to be 75% (70–80%) of farmers fattening pigs for the "formal" value chain (not those destined for "backyard" slaughter)
- Vaccination and treatment at 3 and 6 months (2 doses) is 100% protective (8, 61), but 1% of treatments may fail through user error
- Vaccination and treatment failure will result in infection profiles equivalent to non-treated pigs (i.e., Proportion of light/medium/heavy infections will be equivalent)
- Meat inspectors will be present at every formal slaughter facility and inspect every pig presented
- The proportion of pigs destined for the informal sector from fattening remains at the baseline level and these farmers do not take up the pharmaceutical intervention.
- Pigs slaughtered in the informal sector obtain only 45% of the price of a formally slaughtered pig (62).

The updated model can be found in **Supplementary Material S1**. The new model parameters are described in **Table 1** and the original model parameters are presented in Thomas et al. (49). Ten additional scenarios were added to the original 15 detailed in the original model (49) and are described as follows:

Scenario 1 = Pig is formally slaughtered/treated/lightly infected/not detected at meat inspection
Scenario 2 = Pig is formally slaughtered/treated/lightly infected/detected at meat inspection/condemned
Scenario 3 = Pig is formally slaughtered/treated/moderately infected/not detected at meat inspection
Scenario 4 = Pig is formally slaughtered/treated/moderately infected/detected at meat inspection/condemned
Scenario 5 = Pig is formally slaughtered/treated/heavily infected/not detected at meat inspection
Scenario 6 = Pig is formally slaughtered/treated/heavily infected/detected at meat inspection/condemned
Scenario 7 = Pig is formally slaughtered/treated/very heavily infected/not detected at meat inspection
Scenario 8 = Pig is formally slaughtered/treated/very heavily infected/detected at meat inspection/condemned
Scenario 9 = Pig is formally slaughtered/treated/uninfected/not detected at meat inspection
Scenario 10 = Pig is formally slaughtered/treated/ uninfected/detected at meat inspection (false positive)/condemned
Scenario 11 = Pig is formally slaughtered/Not treated/lightly infected/not detected at meat inspection
Scenario 12 = Pig is formally slaughtered/Not treated/lightly infected/detected at meat inspection/condemned
Scenario 13 = Pig is formally slaughtered/Not treated/moderately infected/not detected at meat inspection
Scenario 14 = Pig is formally slaughtered/Not treated/moderately infected /not detected at lingual palpation/condemned
Scenario 15 = Pig is formally slaughtered/Not treated/ heavily infected/not detected at meat inspection
Scenario 16 = Pig is formally slaughtered/Not treated/heavily infected/detected at meat inspection/condemned
Scenario 17 = Pig is formally slaughtered/Not treated/very heavily infected/not detected at meat inspection
Scenario 18 = Pig is formally slaughtered/Not treated/very heavily infected/detected at meat inspection/condemned
Scenario 19 = Pig is formally slaughtered/Not treated/uninfected/ not detected at meat inspection

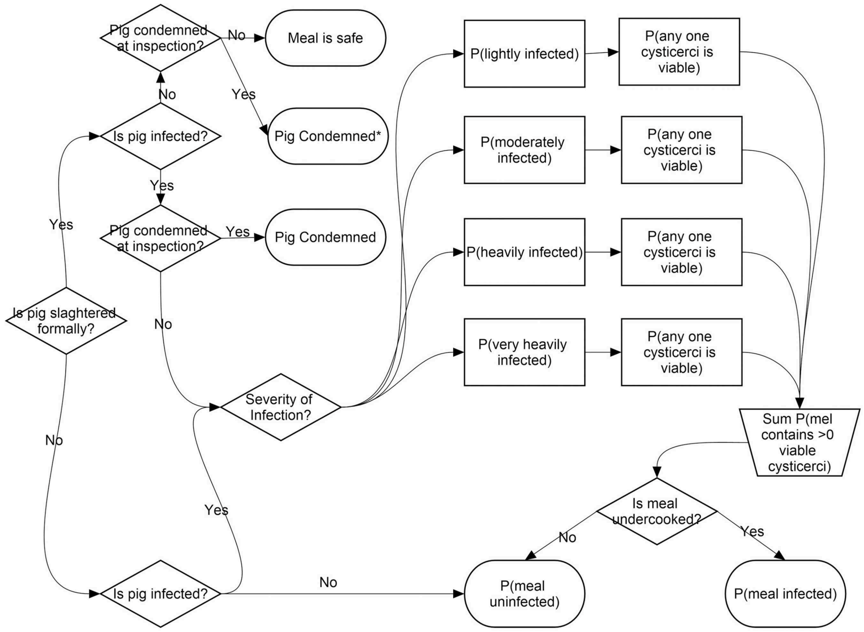

FIGURE 1 | Food chain risk model structure © 2017 Thomas et al. Reproduced from Thomas et al. (49).

Scenario 20 = Pig is formally slaughtered/Not treated/ uninfected/detected at meat inspection (false positive)/condemned
Scenario 21 = Pig is informally slaughtered/not treated/ lightly infected
Scenario 22 = Pig is informally slaughtered/not treated/ moderately infected
Scenario 23 = Pig is informally slaughtered/not treated/ heavily infected
Scenario 24 = Pig is informally slaughtered/not treated/ v. heavily infected
Scenario 25 = Pig is informally slaughtered/not treated/ uninfected

The probability of each scenario described is calculated as follows:

$$\begin{aligned} \text{P(scenario x)} &= (\text{P(formal/informal slaughter)}^{*}\text{P(treated)} \\ &\quad {}^{*}(\text{P(Infected/uninfected)}^{*}\text{P(severity of infection)} \\ &\quad {}^{*}\text{P(detected/undetected at meat inspection))} \end{aligned}$$

And the probability of any one meal being potentially infective at consumption expressed as:

$$\begin{aligned} &\text{P(anyoneporkmealisinfectiveatconsumption)} \\ &= ((\text{P(pork meal contains a cyst| Situation1)}^{*}\text{P(Situation1)} \\ &+ \text{P(pork meal contains a cyst|Situation2)}^{*}\text{P(Situation2)} \\ &+ \text{P(pork meal contains a cyst|Situation3)}^{*}\text{P(Situation3)......} \\ &+ \text{P(pork meal contains a cyst|Situation36)}^{*}\text{P(Situation36))} \\ &\quad {}^{*}\text{P(anyonecystisviablepriortocooking))}^{*}\text{P(Meal undercooked)} \end{aligned}$$

Only partial costs to the pig industry were considered in this analysis, including; the vaccination and treatment protocol, and losses due to carcass condemnation (pork price/kg × carcass weight), feeding and transport of pigs were not included. Costs to the county government considered are the additional cost of staffing all pork slaughter facilities with a qualified meat inspector. The income from meat inspection fees ($1.4 per pig) were not included as these are currently paid for every pig irrespective of the presence of a meat inspector. The interventions are compared through their incremental cost-effectiveness analysis (ICER), calculated according to the equation (65)

$$ICER = \frac{(\text{Cost of strategy} - \text{Cost current strategy})}{(\text{Effectiveness of strategy} - \text{Effectiveness current strategy})}$$

Where: Costs are in US$ at 2017 values

A sensitivity analysis was conducted according to the method described previously (49) to determine the most influential parameters on the ICER output.

RESULTS

The models converged after 48,900 iterations, a summary of the results can be found in **Table 2**. All model inputs and outputs can be found in **Supplementary Table 1** (improved meat inspection only) and **Supplementary Table 2** (Meat inspection and treatment protocol).

The model suggests that within the context of an improved meat hygiene service, addition of a vaccination and treatment

TABLE 1 | New model parameters. Parameters P1–P25 as per original model (49).

Parameter	Description	Source	Probability	Distribution
P26	Probability infected pig is detected and condemned at inspection	Sensitivity and Specificity of inspection (46)	0.387 (97.5% C.I 0.22–0.58) Sensitivity	BetaPert (0.1, 0.387, 0.9)
P27	Probability uninfected pig passes inspection		1.0 (97.5% C.I. 0.9-1.0)	BetaPert (0.9, 1.0, 1.0)
P28	Probability pig slaughtered formally has undergone vaccination and treatment protocol	Assumption	0.75	Uniform (0.7-0.8)
P29	Probability pig is not infective after vaccination and treatment protocol	100% effective (8, 61) potential for 1% treatment error	1.0 (0.99–1.0)	BetaPert (0.99, 1.0, 1.0)
P30	Value of carcass at slaughter	Mean dressed-weight 22.5kg (63) Pork price/kg Per. Comms. M.K Murungi, 2018 $3.2	Calculated as dressed-weight × pork price (Static)	
P31	Average daily weight gain	(64)	110 g/day (80–140 g)	BetaPert (80, 110, 130)
P32	Pig live-weight at 3mths		Calculated 8 kg weaned weight + [(P30*30)*2]	
P33	Pig live-weight at 6mths		Calculated as P32 + [(P30*30)*3]	
P34	Cost of 1 dose Cysvax (IIL India)	Per. Comms. M. Lightowlers 2018	$0.5	Static
P35	Cost of oxfendazole treatment/kg (Paranthic from MCI Morocco)		$0.00038	Static
P36	Cost of vaccination and treatment protocol per pig	2 doses of Cysvax and 2 treatments with oxfendazole 30 mg/kg (8)	Calculated as (P34 × 2) + (P35*32) + (P35*P33)	
P37	Number of meat inspectors required to fill deficit in Busia county	Dr Ogendo, County Director of Veterinary Services 2018	24	Static
P38	Global cost per meat inspector (salary, motorbike, ancillary costs)		$164,100	RiskPert(6400,7000,7900)4
P39	Meat Inspection costs		Calculated as P38*P37	

protocol in pigs has the potential to improve the cost-effectiveness of the intervention by 74.6% from $59 (99% U.I $15–$402) to $15 (99% U.I.$ 9.81–$33.75) per infective meal avoided. For farmers, the cost-benefit ratio for adopting the vaccination and treatment protocol is 10.29, due to the resultant reduction in condemnation losses, without considering the potential additional benefits from increase in weight-gain though treatment of gastro-intestinal nematode infections.

Spearmans rank order coefficients (ρ) indicated that the five most influential inputs on the ICER were; the probability of any one cysticercus being viable ($\rho = 0.76$), the probability that an uninfected pig is correctly passed at meat inspection ($\rho = -0.26$), the probability that an untreated pig is infected ($\rho = 0.22$), the probability of a pig being treated ($\rho = -0.18$) and the mean number of cysts in a heavily infected pig ($\rho = 0.17$). These five parameters were included in an advanced sensitivity analysis. If all other parameters are fixed, the probability of any one cyst being viable has the largest influence over the ICER, with the mean at 1% of the input value being $11.06 and at 99% of the input value being $22.4.

DISCUSSION

The analysis indicates that from a societal perspective, implementing a vaccination and treatment protocol in pigs has the potential to enhance the incremental cost-effectiveness ratio ($/potential infective event avoided) of a *T. solium* control intervention based on enforcing meat inspection regulations. It also indicates the potential for public sector investment, in this case in the meat hygiene inspectorate, to leverage private sector investment, e.g., in a vaccination and treatment protocol for pigs, to "insure" the private sector against potential losses due to regulatory standards.

Within the immediate aftermath of tightening meat hygiene regulations it is expected that food producers will incur a degree of financial loss as they adapt to the new regulatory environment (66). Increased costs may relate to carcass or partial carcass condemnation, or from the increased time required for stringent meat inspection to occur. However, it would also be expected that over time these losses would reduce and stabilize as the market adapts to the new environment, with pork traders and butchers seeking pigs from "improved" producers, or pre-screening pigs for infection prior to purchase, in order to reduce their risk. Screening of pigs by pork traders using lingual palpation has already been reported in Tanzania (67) and Zambia (62) and traders in Kenya have expressed an interest in "insurance" against condemnation (47).

Providing small-scale farmers with the responsibility and agency to bring a safe product to market is an important aspect of improving and growing a viable pig industry in *T. solium* endemic areas. How farmers address the problem of *T. solium,* alongside other animal health and husbandry

TABLE 2 | Model outputs.

	Baseline (no pigs inspected) (49)	All pigs presented for slaughter at registered facilities ("formal slaughter") are inspected	Farmers utilize treatment protocol for those pigs entering the formal system
Estimated risk of infection from any one pork meal consumed	0.006 (99% Uncertainty Interval (U.I). 0.0002–0.0164)	0.0036 (99% U.I 0.00009–0.0118)	0.0012 (99% UI. 0.00003–0.0041)
Number of infective events/year in Busia county	22,282* (99% U.I. 622±64,134)	14,709 (99% U.I. 368-52,209)	5,121 (99% U.I. 118-18,087)
Potentially infective events avoided from baseline	N/A	7,500 (one-sided 99% U.I 0-21,912)	17,161 (99% U.I. 504-46,047)
Losses through condemnation of carcasses	$10,665* (99% U.I. 652-32,200)	$196,078 (99% UI 63,067–395,189)	$67,143 (99% U.I 19.936–138,946)
Total treatment costs	N/A	N/A	$17,363 (99% U.I. 14,828–19,825)
Cost to county government for meat inspection services	$112,817 (99% U.I. 103,712–123,658)	$282,043 (99% U.I. $259,279–$309,146)	$282,043 (99% U.I. $259,279–$309,146)
Condemnation losses avoided through treatment	N/A	N/A	$178,724 (99% U.I. 48,239–375,364)
Incremental cost of intervention from baseline	N/A	$354,730 (99% U.I. 219,694–$555,247)	$239, 102 (99% U.I. $178,999–$352,102)
ICER ($/infective event avoided)	N/A	$59 (99% U.I $15–$402)	$15 (99% U.I.$ 9.81–$33.75)

**Fixed as a static baseline for comparison with intervention models.*

issues they may be facing, is essentially an individual decision and the solutions chosen must be relevant to the context in which they are operating. Encouraging farmers to invest in *T. solium* control interventions may require a "carrot and stick" approach including enforcement of meat hygiene regulations and promotion of the potential profits afforded by producing "safe" pork.

A combination of rewards and punishments, "carrots and sticks," have been demonstrated to have a stronger effect on eliciting "correct" behavior, than either alone (68). In terms of rewards to the farmer for adopting such pharmaceuticals there are two potential ways in which revenue may be enhanced. The use of oxfendazole also has the potential to improve the profitability of pig farming through the treatment of the gastro-intestinal nematode infections which are prevalent in many small-holder pig systems. An overall gastro-intestinal nematode prevalence of 91% was detected in small-holder pigs in Uganda (69) and of 84.2% in western Kenya (70). Treatment of these infections should lead to improvement in the feed conversion efficiency of these pigs, leading to increased daily weight gain, as has been demonstrated in cattle (71).

Rewards may also come in the form of a price premium, or enhanced market access, for a high quality product, the goal of many private food standards. Willingness-to-pay for pork perceived to be "safe" has been previously demonstrated in China (72), but the ability to pay a "safe pork" premium assumes a level of disposable income which will allow a degree of inelasticity of demand.

In China, where pork is a traditional component of the diet, the price elasticity of pork has been shown to be low (73). In sub-Saharan Africa pork is not a traditional food, though as populations urbanize and incomes rise there is a rapid increase in the volume of pork consumed in the region (74). In Kenya the price elasticity of pork across rural and urban households was also found to be inelastic at 0.96, although closer to the threshold for a "luxury good" than beef, chicken, and goat (75).

Consumption of pork in much of the region is still predominately the domain of those in the upper income brackets. In Kigali, Rwanda for instance pork has been referred to as "Benz" (as in Mercedes Benz) designating it as a high-status product (76), in Uganda the consumption of pork has been shown to be significantly higher among families of higher socio-economic status (77). Within this demographic there may be an ability to pay such a "safe pork premium," but willingness-to-pay for safe food is not only a product of consumer incomes, but of education, risk perception, cultural food preferences, and access to substitute foodstuffs or food suppliers (72, 78).

Although the model presented here is of course only an approximation of reality, with many assumptions incorporated, it illustrates how providing pig farmers with access to pharmaceutical products such as the Cysvax vaccine and oxfendazole, could substantially reduce exposure of consumers to a dangerous zoonotic infection as well as reduce potential losses to the pork industry from the condemnation of pig carcasses, or through the sale of infected pork through the "informal" sector, assuming that these pigs obtain only 45% of the market value (62).

Field trials have indicated the efficacy of the vaccination and treatment protocol to reduce the prevalence of porcine cysticercosis (43, 61, 79). Studies are now needed to establish farmers' willingness-to-pay for these pharmaceutical products and the likelihood of uptake in the context of different regulatory frameworks. In order to allow smallholder farmers in endemic areas to adopt vaccination and treatment protocols, products must be available through local suppliers of agro-veterinary products, they must be appropriately packaged in appropriate dosages for smallholder famers who own 1–5 pigs and sufficient extension services should be provided to raise awareness of the products.

Protecting the food chain through meat inspection requires that countries formulate and enact appropriate meat hygiene legislation and also that sufficient staff are deployed and facilitated including across potentially inaccessible rural areas. Within the analysis presented here, the total cost of meat inspection services has been allocated to *T. solium* control, although these services provide goods far beyond this goal. Meat inspection, including *ante mortem* inspection of the animals arriving for slaughter, provides wider benefits than purely cysticercosis control. By removing diseased animals from the food chain, inspection aims to both reduce zoonotic disease exposure to people and to assist in the detection and control of some livestock diseases thereby providing public goods, which cannot be appropriated by any one individual, to both consumers and the livestock sectors, respectively (80). Meat inspectors, or official veterinarians at meat processing facilities, also have a role in ensuring facility hygiene, a role which provides possibly the most important control on microbial contamination of meat products (81).

Regulatory impact assessments and cost-benefit analysis of meat hygiene regulations would be highly useful for policy makers within endemic counties to enable more efficient allocation of resources within already stretched public budgets. Meat inspectors in Kenya are also trained animal health assistants and their role also incorporates aspects of farm extension and surveillance activities. Ongoing work in western Kenya on the surveillance of zoonotic diseases will enable us to begin quantifying the cost-effectiveness of deploying these professional resources across a range of different surveillance and extension activities. Providing economic data will allow countries to prioritize interventions for the NTDs as they move into the next phase of the roadmap to 2030 (82).

CONCLUSIONS

Through the use of a stochastic risk model, we have demonstrated how within the context of enforced meat hygiene legislation, adoption of a porcine vaccination and treatment protocol by farmers may provide a quantifiable economic benefit to the pig industry through a reduction in losses through condemnation. A porcine formulation of oxfendazole (as Paranthic 10%) and TSOL18 (Cysvax) are now in commercial production and licensing is underway in several sub-Saharan African countries, including Kenya. Programmes are now urgently needed to provide access to these products to those who require them, stimulate demand and monitor the uptake and cost-effectiveness of these products if we are to be successful in the global goal to control this important zoonotic parasite.

AUTHOR CONTRIBUTIONS

LT conceived and produced a first draft of the manuscript. EC, EF, and JR were involved in the development of the ideas presented in the manuscript and assisted in the writing. All authors read and approved the final draft of 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.2019.00176/full#supplementary-material

Supplementary Material S1 | Adapted food chain risk model. Available online at: https://figshare.com/s/42e6a65deaafc72e1cb6.

Supplementary Table 1 | Model inputs and outputs improved meat inspection only.

Supplementary Table 2 | Model inputs and outputs improved meat inspection and pharmacological inputs.

REFERENCES

1. Carabin H, Ndimubanzi PC, Budke CM, Nguyen H, Qian Y, Cowan LD, et al. Clinical manifestations associated with neurocysticercosis: a systematic review. *PLoS Negl Trop Dis.* (2011) 5:e1152. doi: 10.1371/journal.pntd.0001152
2. Carabin H, Krecek RC, Cowan LD, Michael LM, Foyaca-Sibat H, Nash TE, et al. Estimation of the cost of *Taenia solium* cysticercosis in

Eastern Cape Province, South Africa. *Trop Med Int Health.* (2006) 11:906–16. doi: 10.1111/j.1365-3156.2006.01627.x
3. Bhattarai R, Budke CM, Carabin H, Proaño JV, Flores-Rivera J, Corona T, et al. Estimating the non-monetary burden of neurocysticercosis in Mexico. *PLoS Negl Trop Dis.* (2012) 6:e1521. doi: 10.1371/journal.pntd.0001521
4. World Health Organization. *Accelerating Work To Overcome The Global Impact of Neglected Tropical Diseases: A Roadmap for Implementation.* Geneva: WHO (2012).
5. Okello AL, Thomas LF. Human taeniasis: current insights into prevention and management strategies in endemic countries. *Risk Manage Healthcare Policy.* (2017) 10:107. doi: 10.2147/RMHP.S116545
6. Carabin H, Traoré AA. *Taenia solium* taeniasis and cysticercosis control and elimination through community-based interventions. *Curr Trop Med Rep.* (2014) 1:181–93. doi: 10.1007/s40475-014-0029-4
7. Thomas LF. Landscape analysis: control of *Taenia solium.* Geneva: World Health Organization (2015).
8. Lightowlers MW, Donadeu M. Designing a minimal intervention strategy to control *Taenia solium*. *Trends Parasitol.* (2017) 33:426–34. doi: 10.1016/j.pt.2017.01.011
9. Bobes RJ, Fragoso G, Fleury A, García-Varela M, Sciutto E, Larralde C, et al. Evolution, molecular epidemiology and perspectives on the research of taeniid parasites with special emphasis on *Taenia solium*. *Infect Genet Evol.* (2014) 23:150–60. doi: 10.1016/j.meegid.2014.02.005
10. Yanagida T, Carod J-F, Sako Y, Nakao M, Hoberg EP, Ito A. Genetics of the pig tapeworm in Madagascar reveal a history of human dispersal and colonization. *PLoS ONE.* (2014) 9:e109002. doi: 10.1371/journal.pone.0109002
11. Garcia HH, Gonzalez AE, Evans AWC, Gilman RH. *Taenia solium* cysticercosis. *Lancet.* (2003) 362:547–56. doi: 10.1016/S0140-6736(03)14117-7
12. Debacq G, Moyano LM, Garcia HH, Boumediene F, Marin B, Ngoungou EB, et al. Systematic review and meta-analysis estimating association of cysticercosis and neurocysticercosis with epilepsy. *PLoS Neglect Trop Dis.* (2017) 11:e0005153. doi: 10.1371/journal.pntd.0005153
13. Nau AL, Mwape KE, Wiefek J, Schmidt K, Abatih E, Dorny P, et al. Cognitive impairment and quality of life of people with epilepsy and neurocysticercosis in Zambia. *Epilepsy Behav.* (2018) 80:354–9. doi: 10.1016/j.yebeh.2017.10.042
14. Torgerson PR, Devleesschauwer B, Praet N, Speybroeck N, Willingham AL, Kasuga F, et al. World health organization estimates of the global and regional disease burden of 11 foodborne parasitic diseases, 2010: a data synthesis. *PLoS Med.* (2015) 12:e1001920. doi: 10.1371/journal.pmed.1001920
15. Ito A, Yanagida T, Nakao M. Recent advances and perspectives in molecular epidemiology of *Taenia solium* cysticercosis. *Infect Genet Evol.* (2015) 40:57–367 doi: 10.1016/j.meegid.2015.06.022
16. Coral-Almeida M, Gabriël S, Abatih EN, Praet N, Benitez W, Dorny P. *Taenia solium* human cysticercosis: a systematic review of sero-epidemiological data from endemic zones around the world. *PLoS Negl Trop Dis.* (2015) 9:e0003919. doi: 10.1371/journal.pntd.0003919
17. Devleesschauwer B, Allepuz A, Dermauw V, Johansen MV, Laranjo-González M, Smit SAG, et al. *Taenia solium* in Europe: still endemic? *Acta Trop.* (2017) 165:96–9. doi: 10.1016/j.actatropica.2015.08.006
18. Raghava MV, Prabhakaran V, Jayaraman T, Muliyil J, Oommen A, Dorny P, et al. Detecting spatial clusters of Taenia solium infections in a rural block in South India. *Trans R Soc Trop Med Hygiene.* (2010) 104:601–12. doi: 10.1016/j.trstmh.2010.06.002
19. World Health Organization. Intensifying control of neglected diseases. In: Daurmerie KM, DK, editors. *International Workshop on the Intensified Control of Neglected Diseases*. Berlin: WHO Communicable Diseases (2003).
20. World Health Organization. *The Control of Neglected Zoonotic Diseases: A Route to Poverty Alleviation.* Geneva: WHO (2006), p. 65.
21. World Health Organization. *Integrated Control of Neglected Diseases in Afric: Applying the "One Health" Concept.* Nairobi: WHO, ILRI (2007).
22. World Health Organization. *The Control of Neglected Zoonotic Diseases: From Advocacy to Action: Report of the Fourth International Meeting Held at WHO Headquarters,* 19-20 November 2014. Geneva: WHO (2015).
23. U. T. C. Diseases NT. *London Declaration on Neglected Tropical Diseases.* (2012). Available online at: https://unitingtocombatntds.org/london-declaration-neglected-tropical-diseases/.
24. World Health Organization. *Accelerating Work to Overcome the Global Impact of Neglected Tropical Diseases: A Roadmap for Implementation: Executive Summary*. Geneva: World Health Organization (2012). (accessed October 1, 2018).
25. World Health Assembly. *WHA66. 12: Neglected Tropical Diseases*. World Health Organization (2013).
26. De Coster T, Van Damme I, Baauw J, Gabriël S. Recent advancements in the control of *Taenia solium*: a systematic review. *Food Waterborne Parasitol.* (2018) 13:e00030. doi: 10.1016/j.fawpar.2018.e00030
27. Gemmell M. A critical approach to the concepts of control and eradication of echinococcosis/hydatidosis and taeniasis/cysticercosis. *Int J Parasitol.* (1987) 17:465–72. doi: 10.1016/0020-7519(87)90122-6
28. Sotelo J, Rosas N, Palencia G. Freezing of infested pork muscle kills cysticerci. *JAMA.* (1986) 256:893–94. doi: 10.1001/jama.256.7.893
29. Flores-Pérez I, Gonzalez GF, Sciutto E, de Aluja AS. Apoptosis induced by gamma irradiation of *Taenia solium* metacestodes. *Parasitol Res.* (2003) 90:203–8. doi: 10.1007/s00436-002-0819-9
30. Rodríguez-Canul R, Argáez-Rodríguez F, Pacheco de la Gala D, Villegas-Perez S, Fraser A, Craig P, et al. *Taenia solium* metacestode viability in infected pork after preparation with salt pickling or cooking methods common in Yucatan, Mexico. *J Food Protect.* (2002) 65:666–9. doi: 10.4315/0362-028X-65.4.666
31. Flisser A, Avidan Y, Laiter S, Mintz D, Ongay H. Effect of physical and chemical agents on the viability of the cysticercus of *Taenia solium*. *Salud publica Mexico.* (1986) 28:551.
32. Gamble H. Parasites associated with pork and pork products. *Rev Sci Tech.* (1997) 16:496–506. doi: 10.20506/rst.16.2.1032
33. Bollaerts KE, Messens W, Delhalle L, Aerts M, Van der Stede Y, Dewulf J, et al. Development of a quantitative microbial risk assessment for human salmonellosis through household consumption of fresh minced pork meat in Belgium. *Risk Analysis Int J.* (2009) 29:820–40. doi: 10.1111/j.1539-6924.2009.01223.x
34. Gonzales-Barron U, Redmond G, Butler F. A consumer-phase exposure assessment of *Salmonella Typhimurium* from Irish fresh pork sausages: ICooking I, and consumption modules. *Food Control.* (2010) 21:1693–702. doi: 10.1016/j.foodcont.2010.05.012
35. Carabin H, Millogo A, Ngowi HA, Bauer C, Dermauw V, Koné AC, et al. Effectiveness of a community-based educational programme in reducing the cumulative incidence and prevalence of human *Taenia solium* cysticercosis in Burkina Faso in 2011–14 (EFECAB): a cluster-randomised controlled trial. *Lancet Global Health.* (2018) 6:e411–25. doi: 10.1016/S2214-109X(18)30027-5
36. Johansen MV, Trevisan C, GabriËl S, Magnussen P, Braae UC. Are we ready for *Taenia solium* cysticercosis elimination in sub-Saharan Africa? *Parasitology.* (2017) 144:59–64. doi: 10.1017/S0031182016000500
37. Braae UC, Gabriël S, Trevisan C, Thomas LF, Magnussen P, Abela-Ridder B, et al. Stepwise approach for the control and eventual elimination of *Taenia solium* as a public health problem. *BMC Infect Dis.* (2019) 19:182. doi: 10.1186/s12879-019-3812-y
38. Okello WO, Okello AL, Inthavong P, Tiemann T, Phengsivalouk A, Devleesschauwer B, et al. Improved methods to capture the total societal benefits of zoonotic disease control: demonstrating the cost-effectiveness of an integrated control programme for *Taenia solium*, soil transmitted helminths and classical swine fever in northern Lao PDR. *PLoS Neglect Trop Dis.* (2018) 12:e0006782. doi: 10.1371/journal.pntd.0006782
39. Ngowi HA, Mlangwa JED, Carabin H, Mlozi MRS, Kassuku AA, Kimera SI, et al. Financial efficiency of health and pig management education intervention

in controlling porcine cysticercosis in Mbulu District, northern Tanzania. *Livestock Res Rural Dev.* (2007) 19. Available online at: http://www.lrrd.org/lrrd19/5/ngow19062.htm
40. Welburn S, Beange I, Ducrotoy M, Okello A. The neglected zoonoses—the case for integrated control and advocacy. *Clin Microb Infect.* (2015) 21:433–43. doi: 10.1016/j.cmi.2015.04.011
41. Assana E, Amadou F, Thys E, Lightowlers MW, Zoli AP, Dorny P, et al. Pig-farming systems and porcine cysticercosis in the north of Cameroon. *J Helminthol.* (2010) 84:441–6. doi: 10.1017/S0022149X10000167
42. Alvarez L, Saumell C, Fusé L, Moreno L, Ceballos L, Domingue G, et al. Efficacy of a single high oxfendazole dose against gastrointestinal nematodes in naturally infected pigs. *Vet Parasitol.* (2013) 194:70–4. doi: 10.1016/j.vetpar.2013.01.003
43. Poudel I, Sah K, Subedi S, Singh DK, Kushwaha P, Colston A, et al. Implementation of a practical and effective pilot intervention against transmission of *Taenia solium.* by pigs in the Banke district of Nepal. *PLoS Neglect Trop Dis.* (2019) 13:e0006838. doi: 10.1371/journal.pntd.0006838
44. Okello AL, Thomas L, Inthavong P, Ash A, Khamlome B, Keokamphet C, et al. Assessing the impact of a joint human-porcine intervention package for *Taenia solium.* control: results of a pilot study from northern Lao PDR. *Acta Tropica.* (2016) 159:185–91. doi: 10.1016/j.actatropica.2016.03.012
45. Wabacha JK, Maribei JM, Mulei CM, Kyule MN, Zessin KH, Oluoch-Kosura W. Characterisation of smallholder pig production in Kikuyu Division, central Kenya. *Prevent Vet Med.* (2004) 63:183–95. doi: 10.1016/j.prevetmed.2004.02.007
46. Dorny P, Phiri IK, Vercruysse J, Gabriel S, Willingham Iii AL, Brandt J, et al. A Bayesian approach for estimating values for prevalence and diagnostic test characteristics of porcine cysticercosis. *Int J Parasitol.* (2004) 34:569–76. doi: 10.1016/j.ijpara.2003.11.014
47. Levy M, Dewey C, Poljak Z, Weersink A, Mutua F. Comparing the operations and challenges of pig butchers in rural and peri-urban settings of western Kenya. *Afr J Agric Res.* (2014) 9:125–36. doi: 10.5897/AJAR12.2174
48. Jaffee S, Henson S, Unnevehr L, Grace D, Cassou E. *The Safe Food Imperative.* Washington, DC: World Bank (2018).
49. Thomas LF, de Glanville WA, Cook EA, Barend MDC, Handel I, Wamae CN, et al. Modelling the risk of *Taenia solium* exposure from pork produced in western Kenya. *PLoS Neglect Trop Dis.* (2017) 11:e0005371. doi: 10.1371/journal.pntd.0005371
50. Fèvre EM, Glanville WA, Thomas LF, Cook EA, Kariuki S, Wamae CN. An integrated study of human and animal infectious disease in the Lake Victoria crescent small-holder crop-livestock production system, Kenya. *BMC Infect Dis.* (2017) 17:457. doi: 10.1186/s12879-017-2559-6
51. Thomas LF, Harrison LJS, Toye P, de Glanville WA, Cook EAJ, Wamae CN, et al. Prevalence of *Taenia solium.* cysticercosis in pigs entering the food chain in western Kenya. *Trop Animal Health Prod.* (2015) 48:1–6. doi: 10.1007/s11250-015-0949-6
52. Thomas LF. *Epidemiology of Taenia solium Cysticercosis in Western Kenya School of Biological Sciences.* University of Edinburgh (2014).
53. Carter NA, Dewey CE, Thomas LF, Lukuyu B, Grace D, de Lange C. Nutrient requirements and low-cost balanced diets, based on seasonally available local feedstuffs, for local pigs on smallholder farms in Western Kenya. *Trop Anim Health Prod.* (2016) 48:337–47. doi: 10.1007/s11250-015-0957-6
54. Kagira JM, Kanyari PN, Maingi N, Githigia SM, Ng'ang'a JC, Karuga JW. Characteristics of the smallholder free-range pig production system in western Kenya. *Trop Anim Health Prod.* (2010) 42:865–73. doi: 10.1007/s11250-009-9500-y
55. Tiemann TT, Phengvilaysouk A, Keonouchanh S. Herd dynamics reflect constraints for pig production and farmer attitudes in smallholder systems in Lao PDR. *Animal Prod Sci.* (2017) 58:2158–166. doi: 10.1071/AN16730
56. Braae UC, Penrith M-L, Ngowi H, Lekule F, Johansen MV. Awareness concerning optimal pig production management and animal welfare among smallholder farmers in Tanzania. *Anim Welfare.* (2016) 25:439–46. doi: 10.7120/09627286.25.4.439
57. Phengsavanh P, Ogle B, Stür W, Frankow-Lindberg B, Lindberg J. Smallholder pig rearing systems in Northern Lao PDR. *Asian Australasian J Anim Sci.* (2011) 24:867–74. doi: 10.5713/ajas.2011.10289
58. Tekle T, Tesfay A, Kifleyohannes T. Smallholder pig production and its constraints in Mekelle and southern zone of Tigray region, north Ethiopia. *Livestock Res Rural Dev.* (2013) 25:1–5. Available online at: http://www.lrrd.cipav.org.co/lrrd25/10/tekl25184.htm
59. Chauhan A, Patel B, Maurya R, Kumar S, Shukla S, Kumar S. Pig production system as a source of livelihood in Indian scenario: an overview. *Int J Sci Environ Technol.* (2016) 5:2089–96. Available online at: http://www.ijset.net/index_issue.php?iid=45.
60. Kimbi E, Lekule F, Mlangwa J, Mejer H, Thamsborg S. Smallholder pigs production systems in Tanzania. *J Agric Sci Technol.* (2015) 5:47–60. doi: 10.17265/2161-6256/2015.01A.007
61. Assana E, Kyngdon CT, Gauci CG, Geerts S, Dorny P, De Deken R, et al. Elimination of *Taenia solium* transmission to pigs in a field trial of the TSOL18 vaccine in Cameroon. *Int J Parasitol.* (2010) 40:515–9. doi: 10.1016/j.ijpara.2010.01.006
62. Hobbs EC, Mwape KE, Devleesschauwer B, Gabriël S, Chembensofu M, Mambwe M, et al. *Taenia solium* from a community perspective: preliminary costing data in the Katete and Sinda districts in Eastern Zambia. *Veter Parasitol.* (2018) 251:63–7. doi: 10.1016/j.vetpar.2018.01.001
63. Levy M, Dewey C, Weersink A, Mutua F. Comparative profitability of pig butcher businesses in western Kenya. In: *International Symposia on Veterinary Epidemiology and Economics (ISVEE) proceedings, ISVEE 12: Proceedings of the 12th Symposium of the International Society for Veterinary Epidemiology and Economics,* Durban, (2009).
64. Mutua F, Dewey C, Arimi S, Ogara W, Levy M, Schelling E. A description of local pig feeding systems in village smallholder farms of Western Kenya. *Trop Anim Health Product.* (2012) 44:1157–62. doi: 10.1007/s11250-011-0052-6
65. Detsky AS, Naglie IG. A clinician's guide to cost-effectiveness analysis. *Ann Intern Med.* (1990) 113:147–54. doi: 10.7326/0003-4819-113-2-147
66. Antle JM. Benefits and costs of food safety regulation. *Food Policy.* (1999) 24:605–23. doi: 10.1016/S0306-9192(99)00068-8
67. Trevisan C, Devleesschauwer B, Schmidt V, Winkler AS, Harrison W, Johansen MV. The societal cost of Taenia solium cysticercosis in Tanzania. *Acta Trop.* (2017) 165:141–54. doi: 10.1016/j.actatropica.2015.12.021
68. Andreoni J, Harbaugh W, Vesterlund L. The carrot or the stick: rewards, punishments, and cooperation. *Am Econ Rev.* (2003) 93:893–902. doi: 10.1257/000282803322157142
69. Nissen S, Poulsen IH, Nejsum P, Olsen A, Roepstorff A, Rubaire-Akiiki C, et al. Prevalence of gastrointestinal nematodes in growing pigs in Kabale District in Uganda. *Trop Anim Health Prod.* (2011) 43:567–72. doi: 10.1007/s11250-010-9732-x
70. Kagira JM, Paul NK, Samuel MG, Ndicho M, Ng'ang'a JC, Gachohi JM. Risk factors associated with occurrence of nematodes in free range pigs in Busia District, Kenya. *Trop Anim Health Prod.* (2012) 44:657–64. doi: 10.1007/s11250-011-9951-9
71. Purvis H, Whittier J, Boyles S, Johnson L, Ritchie H, Rust S, et al. Weight gain and reproductive performance of spring-born beef heifer calves intraruminally administered oxfendazole. *J Anim Sci.* (1994) 72:817–23. doi: 10.2527/1994.724817x
72. Lai J, Wang HH, Ortega DL, Widmar NJO. Factoring Chinese consumers' risk perceptions into their willingness to pay for pork safety, environmental stewardship, and animal welfare. *Food Control.* (2018) 85:423–31. doi: 10.1016/j.foodcont.2017.09.032
73. Wu Y, Li E, Samuel SN. Food consumption in urban China: an empirical analysis. *Appl Econ.* (1995) 27:509–15. doi: 10.1080/00036849500000138
74. Robinson T, Pozzi F. Mapping supply and demand for animal-source foods to 2030. *Anim Prod Health Working Paper.* (2011) 2:1–154.
75. Shibia M, Rahman S, Chidmi B. Consumer demand for meat in Kenya: an examination of the linear approximate almost ideal demand system. *Selected Paper Prepared for Presentation at the 2017 Southern Agricultural Economics Association (SAEA) Annual Meetings in Mobile.* Mobile (2017).
76. Peters D. *Assessment of the Potential of Sweet Potato as Livestock Feed in East Africa: Rwanda, Uganda, and Kenya.* The International Potato Center (CIP) in Nairobi (2008).

77. Kikafunda J, Tumwine J. Diet and socio-economic factors and their association with the nutritional status of pre-school children in a low income suburb of Kampala City, Uganda. *East Afr Med J*. (2006) 83:565–74. doi: 10.4314/eamj.v83i10.9470
78. Ngigi M, Okello J, Lagerkvist C, Karanja N, Mburu J. Urban consumers' willingness to pay for quality of leafy vegetables along the value chain: the case of Nairobi kale consumers, Kenya. *Int J Bus Soc Sci.* (2011) 2:208–16. Available online at: http://ijbssnet.com/journal/index/313.
79. Garcia HH, Gonzalez AE, Tsang VC, O'Neal SE, Llanos-Zavalaga F, Gonzalvez G, et al. Elimination of Taenia solium transmission in Northern Peru. *New Engl J Med.* (2016) 374:2335–44. doi: 10.1056/NEJMoa1515520
80. Edwards DS, Johnston AM, Mead GC. Meat inspection: an overview of present practices andfuture trends. *Veter J.* (1997) 154:135–47. doi: 10.1016/S1090-0233(97)80051-2
81. Blagojevic B, Antic D. Assessment of potential contribution of official meat inspection and abattoir process hygiene to biological safety assurance of final beef and pork carcasses. *Food Control.* (2014) 36:174–82. doi: 10.1016/j.foodcont.2013.08.018
82. World Health Organisation. *WHO Launches Global Consultations for a New Roadmap on Neglected Tropical Diseases.* Geneva (2019).

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Risk Attitudes Affect Livestock Biosecurity Decisions With Ramifications for Disease Control in a Simulated Production System

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Hog producers' operational decisions can be informed by an awareness of risks associated with emergent and endemic diseases. Outbreaks of porcine epidemic diarrhea virus (PEDv) have been re-occurring every year since the first onset in 2013 with substantial losses across the hog production supply chain. Interestingly, a decreasing trend in PEDv incidence is visible. We assert that changes in human behaviors may underlie this trend. Disease prevention using biosecurity practices is used to minimize risk of infection but its efficacy is conditional on human behavior and risk attitude. Standard epidemiological models bring important insights into disease dynamics but have limited predictive ability. Since research shows that human behavior plays a driving role in the disease spread process, the explicit inclusion of human behavior into models adds an important dimension to understanding disease spread. Here we analyze PEDv incidence emerging from an agent-based model (ABM) that uses both epidemiological dynamics and algorithms that incorporate heterogeneous human decisions. We investigate the effects of shifting fractions of hog producers between risk tolerant and risk averse positions. These shifts affect the dynamics describing willingness to increase biosecurity as a response to disease threats and, indirectly, change infection probabilities and the resultant intensity and impact of the disease outbreak. Our ABM generates empirically verifiable patterns of PEDv transmission. Scenario results show that relatively small shifts (10% of the producer agents) toward a risk averse position can lead to a significant decrease in total incidence. For significantly steeper decreases in disease incidence, the model's hog producer population needed at least 37.5% of risk averse. Our study provides insight into the link between risk attitude, decisions related to biosecurity, and consequent spread of disease within a livestock production system. We suggest that it is possible to create positive, lasting changes in animal health by nudging the population of livestock producers toward more risk averse behaviors. We make a case for integrating social and epidemiological aspects in disease spread models to test intervention strategies intended to improve biosecurity and animal health at the system scale.

Keywords: agent-based models, disease transmission, biosecurity, risk attitude, human behavior, porcine epidemic diarrhea virus (PEDv), hog production

INTRODUCTION

In recent years, the hog production industry has been subjected to incursions of both endemic and new diseases. In 2013, the first outbreak of porcine epidemic diarrhea virus (PEDv) in the U.S. shook the industry both economically and socially, and required us to rethink effective disease-prevention strategies (1, 2). PEDv is now an endemic disease and it is one of the most severe infectious diseases in the hog industry with ∼80–100% morbidity and 50–90% mortality in suckling piglets (3, 4). The virus can spread via direct, indirect and possibly airborne transmission mechanisms (5–12). Direct transmission involves animal-to-animal contact while indirect transmission implies exposure to contaminated fomites. Furthermore, both animal and environment can be reservoirs of the virus for long periods, making it difficult to predict the time and place of new outbreaks (13). There is no single successful control strategy for PEDv, in part because of the complexity and large size of the swine population, but also because of poorly-understood transmission vectors, including inconsistent, and occasionally-irrational behavior by humans in the industry. Thus, one aspect of the problem has become clear: livestock disease spread is not only epidemiological but also a matter of human behavior, specifically the choices producers make to implement biosecurity protocols or not (14).

Observed data published by the United States Department of Agriculture (Swine Enteric Coronavirus Disease Situation report—Mar 2018[1]) show a high PEDv incidence in the winter of 2014 followed by a significant decreasing trend over each subsequent year (**Figure 1**). The data also exhibit seasonal cycles with winter seasons generally carrying higher PEDv incidence. While there are likely a number of factors influencing the variability in the data, we became interested in the steady decreasing trend. Since the pathways of virus transmission have stayed the same through time, why has incidence decreased? Likely, this is evidence of a change in the response to disease within the production system. We therefore investigate how shifts in human behaviors and risk mitigation strategies longitudinally affect contagion dynamics.

Biosecurity has been considered the most important prevention strategy for PEDv (14). Biosecurity practices such as disinfecting footwear, showering and wearing clean clothes before entering production premises, vehicle washing and disinfecting can be employed to mitigate PEDv transmission both within and between farms (15–17). Although producers have access to biosecurity information and implementation instructions, their risk attitude can influence the willingness to comply with biosecurity protocols (18, 19). Hereafter, we refer to this operational willingness to obey the rules as "compliance" with biosecurity protocols. Failure to comply with biosecurity practices can lead to infection, increased mortality of pigs of all ages and economic losses for the farm. A second aspect of biosecurity is the willingness by managers and owners to invest in biosecurity, for example purchasing truck-washing equipment or installing air-filtration systems. For this reason, human decision-making factors, in addition to epidemiological factors, are essential pieces needed to understand disease dynamics and their associated economic repercussions (20).

From an applied perspective, clarifying the mechanisms that link human risk attitude to biosecurity adoption and compliance will aid in understanding long-term disease risks and help to develop strategies for controlling disease incurrence (21). At the forefront of disease prevention are people involved with daily on-farm practices or decisions regarding the biosecurity standards on a farm. However, not everybody perceives disease risk in

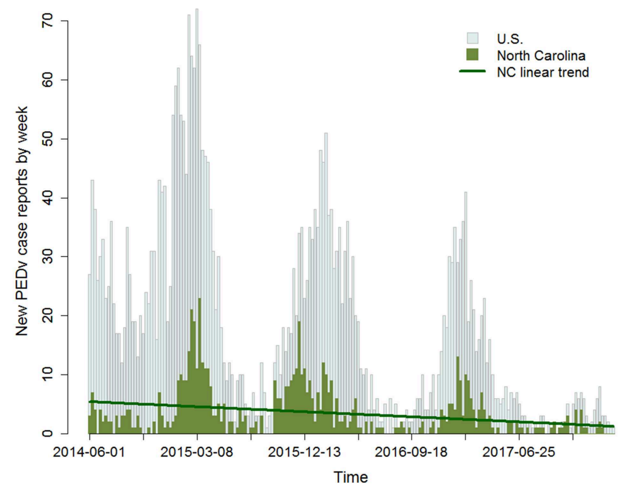

FIGURE 1 | Time series of the number of confirmed new PEDv positive premises by week. Gray bars report data for the U.S. and green bars for the state of North Carolina (NC). The data are available for the period 06/01/2014 to 02/25/2018. Issued on June 5, 2014, a Federal Order required the reporting of swine enteric coronavirus diseases including PEDv (https://www.aasv.org/aasv%20website/Resources/Diseases/PorcineEpidemicDiarrhea.php). On March 6, 2018, USDA rescinded the Federal Order (https://www.aphis.usda.gov/aphis/newsroom/news/sa_by_date/sa-2018/secd-reporting). The dark green line traces the decreasing trend in incidence in NC with a slope $m = -0.02$. This is equivalent to an average decrease from about 20 new cases in the month June, 2014 down to eight new cases in the same month in 2017.

[1] http://www.aphis.usda.gov/animal-health/secd

the same way (20, 22) and biosecurity practices are not applied homogenously and at the same level across farms (23, 24). Critical research on human decision-making shows that behaviors are not immutable and can be nudged toward standards that are more beneficial both for the individual and the larger community (25). In the case of disease for example, both the producer and the production system can benefit from improved disease control by shifting individual producers' behaviors toward higher biosecurity engagement (20). The integration of epidemiological and social disciplines can provide insights (26) on the effect of shifts in human behavior directed at protecting farms from disease incursions.

A useful approach for studying the mechanisms by which both epidemiological and human-behavioral factors affect disease spread is in a simulated environment where factors can be varied and tested for their effects. Epidemiological models describe the biological and environmental components of disease transmission and evolution (5, 10, 27–30) but do not address the role of human behavior in the process of spreading disease between animal production facilities (19). Melding epidemiology with human behavioral science acknowledges that people play a role in maintaining animal health and offers a potentially richer framework to understand the dynamics of disease and inform prevention strategies (18, 26).

Agent-Based Models (ABMs) have been applied to study social phenomena and analyze macroscopic patterns that emerge from the interaction of a number of agents programmed to behave according to specified rules (31, 32). ABMs are computational models that attempt to capture the behavior of autonomous agents within their environment. An ABM usually consists of: (1) Agents, which represent actors characterized by attributes and behaviors; (2) Agent relationships and functions for their interactions and; (3) an environment in which the agents are embedded and with which they can interact. Sometimes agents can be part of a population and share characteristics and/or behaviors. Agents can receive information and/or learn and therefore have adaptive capabilities. The strength of ABMs is the ability to model complex systems from the bottom up with agents that have believable and realistic behaviors (33, 34). In situations characterized by risk as in the onset of a disease outbreak, the heterogeneity of human responses can lead to complex and dynamic outcomes challenging to foresee. Therefore, modeling agents with human-like characteristics including the ability to appraise and respond to events also with non-rational behaviors, is essential for social-ecological studies (18, 35). An example of the potential of ABMs for epidemiological applications came from the Models of Infectious Disease Agent Studies (MIDAS[2]). In this collaborative effort, a set of ABMs was developed to investigate avian flu transmission incorporating epidemiological, environmental and social aspects and has been used to analyze outbreaks, model outcomes of interventions involving human behaviors and shape policies to help reduce the impact of avian influenza (34). Because ABMs allow explicit modeling of decision-making processes, interactions and networks, they represent an effective approach for simulating the system structure of the swine industry, specifically by incorporating both disease dynamics emerging from virus transmission with animal and feed movement, and human decision processes influencing biosecurity and movement interactions.

To form a better view of PEDv disease dynamics with the role of human behavior, we built an ABM at the scale of a regional hog production system. We modeled disease spread among a variety of different agents: (1) producers with different holding types (farrow-to-finish, farrow-to-wean, wean-to-feeder…), (2) feed mills, and (3) slaughter plants. The modeled hog supply chain includes both single- and multi-site production with networks of pig movement and feed deliveries. The other two main ABM components are the epidemiological and human decision-making components. The epidemiological component contains the mechanisms of PEDv transmission (direct and indirect), while the human behavioral component accounts for risk attitude and decision-making that influence biosecurity in the system. The elements of human decision-making and behavior were selected to reflect patterns observed by industry professionals to have major effects on farm biosecurity: (1) psychological distancing (36) that leads to a relaxation of compliance with biosecurity protocols as time passes without experiencing disease; (2) responsiveness to disease presence and; (3) the willingness of farm managers/owners to invest in biosecurity. The explicit inclusion of human behavior into the ABM provides a dimension for accounting for both the willingness to implement preventive biosecurity measures and to comply with them. Thus, with agent-based modeling we can represent the influence of responsiveness, heterogeneity, information exchange, psychological distancing, and interactions of humans and the environment.

This paper presents and compares the disease-spread consequences of human decision-making simulated using an ABM of a swine production system. To this end, we design agent populations with proportionately varied risk attitudes observed from an online digital field experiment. These range from risk averse strategies that allocate more preventative biosecurity during outbreaks to risk tolerant attitudes that gamble with very little biosecurity investment. As the risk attitude influences the agent behavior in our ABM, we analyzed temporal patterns of disease incidence emerging from the simulated scenarios of heterogeneity in risk attitudes within the population of producer agents.

METHODS

The agent-based model (ABM) used in this study was built off a previous ABM called "Regional U.S. Hog Production Network Biosecurity Model" (RUSHPNBM) originally created by Wiltshire et al. (37) and Wiltshire (38). The purpose of these ABMs has been the study of PEDv transmission in swine production systems. The ABMs are developed in AnyLogic[3] software with all functions written in Java[4]. The main developments of the model for the current study include the addition of: (1) seasonal disease cycles; (2)

[2]https://www.epimodels.org/drupal-new/

[3]https://www.anylogic.com

[4]https://www.oracle.com/technetwork/java/index.html

environmental infection events simulating persistence of PEDv in the environment which allowed for reoccurrence of the disease at previously infected sites; (3) on-farm infections from visitor vehicles other than hog or feed trucks; (4) agent adaptive functionalities (e.g., human behavioral processes such as willingness to adopt biosecurity and psychological distancing); (5) risk attitude categories derived from digital field experiments and; (6) webDb database for data input and output. The model's design and implementation relevant for the current study are provided here and further details can be found in the **Supplementary Material** and in Wiltshire (38) and Wiltshire et al. (37). The main idea of the current ABM is to model both forward and feedback processes that describe the influence of (1) human risk attitude on biosecurity choices, (2) biosecurity on the probability of disease transmission, and (3) disease status on human decisions around biosecurity mediated by risk attitude. The ABM's process flow can be divided into a structural, an epidemiological and a human behavioral component (**Figure 2**), described in the following sections. The values of the model parameters are given in the (**Supplementary Material**).

Structural Component: ABM Representation of the Swine Industry

The structural component simulates a hog production system with agents representing production premises, feed mills and slaughter plants. The hog production chain simulated for this study is a system mirroring the density, operation types and sizes of production units found in North Carolina with data provided by the Farm Location and Agricultural Production Simulator (FLAPS) tool which draws from the USDA Census of Agriculture and aerial images (39). Feed mills and slaughter plants were initialized at random locations with numbers obtained from public data and expert advising. Hog production in the U.S. is increasing, which has resulted in increased vertical integration. Multiple sites are used in the production flow with specialized sites for sows, weanlings, growers and finishing pigs, or any combination of these growth stages. The ABM production agents are therefore also characterized by one of six holding types (farrow-to-wean, wean-to-feeder, feeder-to-finish, farrow-to-finish, wean-to-finish, and feeder-to-finish), size (total number of animals), and number of pig batches (groups of pigs of the same age). Other structural parameters include the basic functions of the hog production system such as the process of birth and growth. Birth, growth and movements of pigs are modeled at the group level using batches of pigs of the same age. The production system of the hog industry requires transfer of hogs from one holding type to the next and in the end to the slaughter plant. For instance, in a three-site production system a pig batch moves from farrow-to-wean to wean-to-feeder to feeder-to-finish sites before finally being sent to the slaughter plant. Pig batch movement as well as feed deliveries generate heterogeneous interactions among agents and are included in the ABM using networks of transportation (**Supplementary Figure 1**). These networks are modeled with agents having set trading and service areas according to their industry role and characterized by neighborhood structures.

Epidemiological Component: ABM Representation of Disease Transmission

The ABM epidemiological component is network-based and spatially explicit in that it simulates disease spread via both direct and indirect mechanisms related to the movement of animals and feed across the production network. It is coupled with a stochastic state transition model including Susceptible (S) and Infectious (I) states. Probability functions regulate the transmission of disease in single agent interactions while the network structure of animal and feed movement determine the ultimate pattern of disease spread. Each simulated agent (hog producers, slaughter plants, and feed mills) may become infected (state I) during an interaction with another agent with a probability that depends on the type of interaction, the agent's biosecurity and a seasonality factor. Specifically, each type of movement interaction is associated with an independent probability of infection calculated using a logistic function. The logistic functions describe the infection probability's dependence on the agent's biosecurity with coefficients derived from the estimates provided using expert opinion. The seasonal variability in PEDv infectivity is modeled as a sinusoidal adjustment on the logistic probability function that varies with time and ultimately generates higher infection probabilities in winter and lower in summer. Explicit representation of disease spread mechanisms and functions for our ABM are detailed in the **Supplementary Material** section titled The agent-based model's epidemiological sub-model.

Aside from the movement of contaminated pigs and feed, two additional sources of infection are implemented: (1) from visitors arriving at the production site and (2) from PEDv surviving in the environment within or around a production site (5, 13, 40). In our ABM, we account for the first infection source by simulating events of visitors on the production sites associated with a logistic infection probability function dependent on the producer agent's biosecurity (**Supplementary Tables 1, 3**). To account for the environmental infection, 0.3% of producers are randomly infected during an event scheduled once a year on a day selected from a triangular distribution defined on the range from mid-September to mid-December with mode the first week of November.

Human Behavioral Component: ABM Representation of Biosecurity Decision-Making

We explicitly investigated the importance of capturing human behavior with interaction and feedbacks between humans and the environment. The producer agents in our ABM have adaptive capabilities and are reactive in that they do not learn but simply respond to signals from other agents and the environment. In the model, a population of veterinarian agents is encoded, each with its own network of hog producers. Within the network, the veterinarian tracks the number of hog producers affected by disease and reports it back weekly. The producer agents are encoded with a set of rules to simulate decisions to alter biosecurity at their facility in response to the disease status in their veterinarian network. Our goal was to explore the

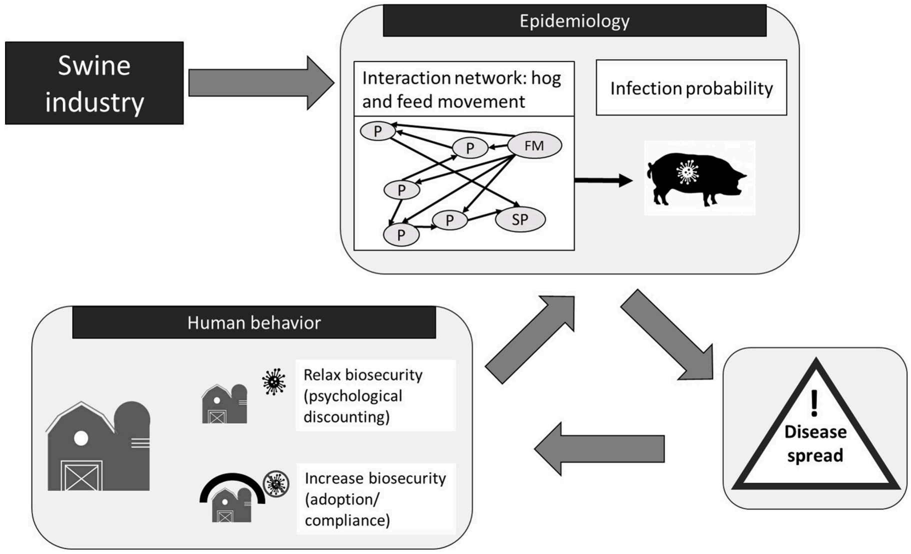

FIGURE 2 | Agent-based model (ABM) process flow. It highlights the ABM's main components and processes of how the Porcine Epidemic Diarrhea virus (PEDv) can spread through the network structure of the swine industry and is influenced by human behavior. The ABM structural component mimics the swine industry with three types of agents: P, producer; FM, feed mill; and SP, slaughter plant. Agents interact via networks of hog and feed movement. The ABM epidemiological component simulates the risk of PEDv transmission associated with movement through these network connections disease spreads. Human decisions on biosecurity also influence infection risk. Disease spread depends on the probability of disease transmission on the networks and influences the biosecurity level on farms.

influence of reactive behaviors on biosecurity and ultimately disease incidence.

To reflect heterogeneity of human risk attitude and allow the evaluation of a variety of human behaviors, the ABM has underlying human processes with parameters for risk attitude, biosecurity investment, responsiveness to disease, and psychological distancing. In particular, the agents' risk-attitude is directly linked to their response to disease by determining the threshold number of neighboring infected production premises necessary for an agent to react and increase its biosecurity with a probability >0.9. We associate risk aversion with higher propensity to adopt biosecurity. For example, risk averse agents almost always increase biosecurity as soon as there are three production premises infected in their veterinarian network. On the opposite side of the risk spectrum, risk tolerant agents increase their biosecurity quasi certainly only when they know that there are nine or more infected production premises in their veterinarian network. In summary, the ABM agent behavior originates from a risk attitude distribution with four categories (risk averse, risk opportunists, risk neutral, and risk tolerant); four forms of disease response, one for each risk attitude category are used to simulate biosecurity response-to-disease strategies; and a utility function for psychological distancing, which simulates the waning of biosecurity compliance since an infection event. The detailed description of parameters and methods for the ABM human behavioral component are provided in the **Supplementary Material** section The agent-based model's human behavioral component.

Risk-Attitude Scenarios Analysis

The goal of this study was to better understand the extent to which shifts in the composition of risk attitudes in the agent population change the incidence of PEDv outbreaks. To this end, we ran a scenario analysis where we shifted fractions of the producer population between risk tolerant and risk averse categories and then evaluated the resulting PEDv incidence. Six model scenarios were compared to a reference baseline scenario (**Table 1**), assigned to the case where the producer population is evenly distributed across all risk attitude categories upon model initialization. The populations of feed mill and slaughter plant agents were kept at even percentages of agents across the four risk attitude groups in all seven scenarios. The baseline scenario in particular was the reference for being the model that we calibrated against observed data. The ABM calibration was performed using AnyLogic software with the built-in genetic algorithm by matching the observed (**Figure 1**) and the simulated PEDv incidence. More information about the calibration methods and results can be found in the **Supplementary Material**, section Calibration of ABM's human behavioral component. For the six alternative scenarios (**Table 1**), all the model parameters were kept fixed at the calibrated values (**Supplementary Table 1**), while the initial proportion of population in the risk attitude groups were varied. For this analysis, the ABM was run over the time period spanning from 12/27/2009 to 02/25/2018. The first part of this period until 05/31/2014 was used to stabilize to model. The period 06/01/2014 to 02/25/2018 overlapping the observations' time series (**Figure 1**) produced the data for the analysis. We executed

TABLE 1 | Risk attitude scenarios.

Scenario	% risk averse producers	% risk tolerant producers
Baseline	25	25
12.5% averse	12.5	37.5
17.5% averse	17.5	32.5
22.5% averse	22.5	27.5
27.5% averse	27.5	22.5
32.5% averse	32.5	17.5
37.5% averse	37.5	12.5

Each scenario represents a different initial condition in the model representing the configuration of risk attitudes in the producer agent population. Columns 2 to 3 report the relative percent of producer agents in each risk attitude group for the seven scenarios. The baseline is the scenario used to calibrate the model. The percentages of producers assigned to the risk neutral and risk averse categories are maintained fixed at 25% in all the scenarios. The increase of risk averse percentage across scenarios aligns with a larger section of the producer population adopting biosecurity with relatively higher probability as a response to disease presence.

Monte Carlo experiments with 800 replicates for the seven separate scenarios and collected disease incidence data.

Statistical analyses on incidence outputs from each scenario were performed using R (41) software. We calculated summary indicators such as total incidence and linear trend coefficients, to characterize the output time series of PEDv incidence and then applied non-parametric statistical tests to compare the indicators across scenarios. Specifically we proceeded in the following ways for each summary indicator:

- Total incidence: It is defined as the sum of incidence over the simulated time period. We built distributions of total incidence from the 800 Monte Carlo replicates for each scenario. We then compared the distributions across scenarios both visually with box-plots and statistically with non-parametric tests. We applied non-parametric tests because the data did not meet either the assumption of normality ($p > 0.0001$ in Shapiro-Wilk test) or the assumption of equal variances ($p > 0.0001$ in both Brown-Forsythe test and Fligner-Killeen test). We first applied the k-sample Anderson-Darling test with all the distributions of total incidence and then compared the distributions pairwise with the two-sample Kolmogorov-Smirnov test. Box-plots were used to show the median, minimum, and maximum values and quantiles of the simulated incidence totals for each scenario.
- Linear trend coefficients: A linear regression model was fit to each of the 800 simulation runs for all scenarios and the values for the coefficients intercept and slope were collected. Box plots of intercept and slope showed the characteristics of the underlying distribution of coefficients' datasets. The non-parametric k-sample Anderson-Darling test followed by the two-sample Kolmogorov-Smirnov test were applied to compare distributions across scenarios because the data did not meet either the assumption of normality (p-value $>$ 0.0001 in Shapiro-Wilk test) or the assumption of equal variances (p-value $>$ 0.0001 in Brown-Forsythe test and Fligner-Killeen test). The Monte Carlo averages of both the simulated incidence and trend coefficients were calculated to display temporal patterns and trends for each scenario.

In all *post hoc* multiple pairwise comparisons with the Kolmogorov-Smirnov test, a Bonferroni adjustment was applied by testing individual hypotheses at the level $\alpha^* = 0.05/21$ (where 21 is the number of tests).

RESULTS

The scenario analysis performed in the study addressed the sensitivity of PEDv incidence outputs given changes in the proportions of producer agents assigned to the risk averse and risk tolerant categories in the ABM. We performed statistical tests to measure the effect of seven distributions of risk attitudes (**Table 1**) on the spread of PEDv within the hog production system simulated in our ABM. The results of the non-parametric tests comparing the distributions of total incidence, linear trend's intercept and slope are shown by the compact letters above the box-plots in **Figures 3–5**. Box-plots are presented to show overall patterns of three indicators and visualize their distribution characteristics across scenarios. The 12.5 and 37.5% averse represent the two extreme scenarios. The baseline is the scenario with an equal percentage (25%) of producers in both the risk averse and risk tolerant categories.

Total Incidence Indicator

The compact letters in **Figure 3** show that there are some significant differences in the distributions of incidence totals across scenarios. All scenarios except for the "22.5% averse" one, which was only 10% less risk averse than the baseline scenario, have distributions significantly different from the baseline scenario. Generally, the scenarios with lower percentage of risk averse producer agents (12.5%, 17.5% averse; compact letter "a") had more simulation runs that produced relatively high incidence totals (larger interquartile ranges) compared to the other scenarios. In contrast, scenario runs with higher proportions of risk averse producer agents (32.5 and 37.5% averse; compact letter "d") lead to significantly different distributions of incidence totals characterized by lower medians and narrower ranges. All the scenarios appear to be right-skewed with some outlying values indicating that in all Monte Carlo experiments there were simulations where the system became very vulnerable to high PEDv infection. This is particularly evident for scenarios 12.5 and 17.5% averse. Overall, the scenarios indicate that the ABM is significantly sensitive to risk attitude shifts as small as 10% producer agents moving from being risk tolerant to being risk averse. Therefore, the total incidence indicator responds to the risk attitude distribution within the population.

The comparative box-plots provided an unexpected result when analyzed in relation to the observed total incidence (**Figure 3**, dashed black line). The ABM tends to underestimate the total incidence. While all scenarios produced some realizations with total incidence close to the observed one, none had the median aligned around the observed total incidence. The scenario with the most risk tolerant producers (12.5% averse) provided the highest number of simulation runs close to the observations in terms of total incidence. These results may suggest that we need to adopt a baseline model that is calibrated on an initial population of producers with relatively

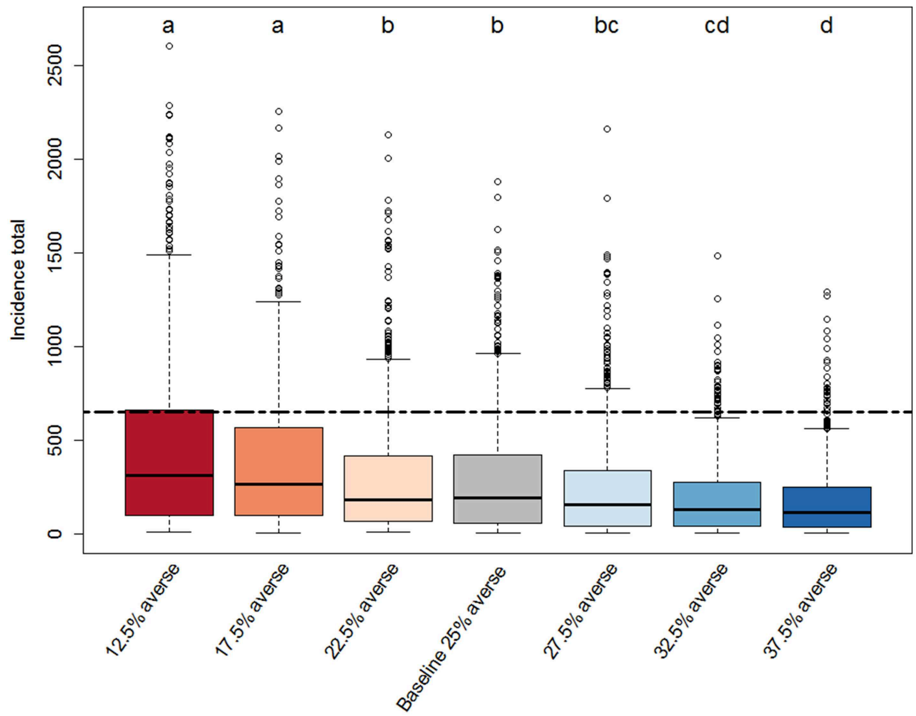

FIGURE 3 | Box-plot of the distributions of total PEDv incidence (sum of new infection cases over the simulated time period) for each scenario. Each scenario represents a different distribution of risk attitudes within the population of producer agents in our ABM. The baseline-scenario population has equal proportions of producer agents in the all four groups (risk averse, risk opportunistic, risk neutral, risk tolerant). Three scenarios (12.5, 17.5, and 22.5% averse) tested the effect of reducing the number of risk averse producers by shifting a fraction (10, 30, or 50%) of producer agents from the risk averse to the risk tolerant category and are color coded with red shades. The other three scenarios (27.5, 32.5, and 37.5% averse) tested the effect of increasing the number of risk averse producers by shifting a fraction (10, 30, or 50%) of producer agents from the risk tolerant to the risk averse category and are color coded with blue shades. Each scenario distribution is drawn from a Monte Carlo experiment with 800 replicates. The compact letter display indicates significance from pairwise comparison. For the scenarios sharing a letter there is no evidence of a difference for that pair of distributions at adjusted $\alpha^* = 0.002$ level (Bonferroni adjustment for 21 comparisons). The black dashed line marks the total incidence in the observed data.

higher percentage of risk tolerant. Alternatively, the current baseline model could be correct and the observed data could represent a rare case that happened to be actualized in reality. Only independent data on risk attitude collected from a sample of producers can help answer this question.

Trend Intercept and Slope Indicators

The linear regressions fit on the incidence data in relations to time provided significant trends (**Table 2**). The R-squared of the linear models are $< 0.2 \pm 0.14$ reflecting the high variability in the data mostly due to the seasonal cycles. Even with the high variability, the data provide significant trends and information about disease incidence change with time. The median *p*-values show significant trend for most of the simulation runs. The average *p*-values further indicate the presence of outlier regressions with non-significant trends. Overall, the data support the existence of significant changes in the incidence with time.

We found significant effects of risk attitude shifts in the coefficients describing the linear trends of incidence through time (**Figures 4**, **5**). In general, the two extreme scenarios (12.5 and 37.5% averse) showed significantly different distributions compared to the baseline scenario. For example, a shift of risk averse agents from 25% (baseline) to 37.5% (more risk averse population) results in a steeper median trend (20% more negative), in other words, disease spread decreases faster. When we look at intercepts, an initial producer population with 37.5% risk averse agents created a situation where the PEDv virus had less infectivity since the simulation start with a median intercept of disease incidence 22% smaller than the intercept of the baseline scenario. We could not claim statistical support for a difference in the distribution of intercepts and slopes between the baseline scenario and the close scenarios (17.5, 22.5, 27.5, and 32.5% averse) except for the case of the intercept distribution for the 17.5% averse scenario (same compact letters in **Figure 4**).

In all scenarios, more than 75% of the simulation runs provided a linear trend with negative slope and positive intercept capturing the same linear trend shown in the observed historical PEDv incidence. This means that most of the simulations reproduced a situation where the disease incidence was higher at start (June 2014) and decreased with time. Fewer runs (<25%) in each scenario showed instead a positive trend indicating some model realizations in which the PEDv outbreak led to a growing incidence through time. These positive-trend cases emerge in the stochastic approach of Monte Carlo experiments where, by the law of large numbers (of simulations) more rare outcomes may also be realized. These cases accentuate and call the attention to

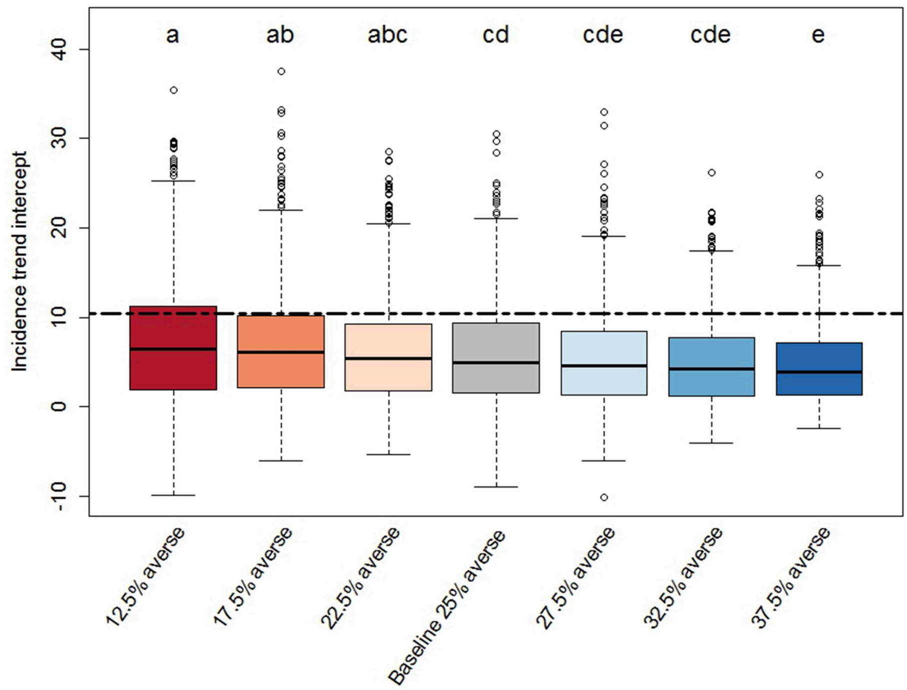

FIGURE 4 | Box-plot of the intercept distributions derived from the PEDv incidence trends for each scenario. Description details as in **Figure 3**.

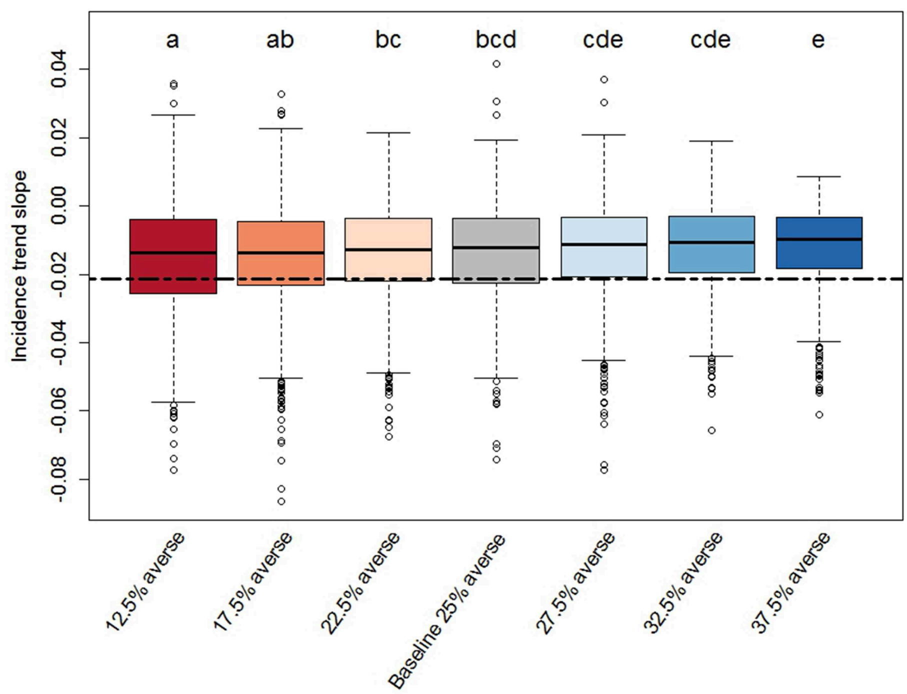

FIGURE 5 | Box-plot of the slope distributions derived from the PEDv incidence trends for each scenario. Description details as in **Figure 3**.

the stochastic nature of disease spread dynamics indicating that there can be unexpected outcomes of disease spread even when the system is calibrated to contain and reduce infection.

The observed intercept and slope falls either outside or at the edge of the inter-quartile range for all the scenarios indicating that most of the model simulations realized a weaker decreasing

TABLE 2 | Regression model fitness indicators.

Scenario	Model R-squared			Model *p*-values		
	Mean	Std. dev.	Median	Mean	Std. dev.	Median
Baseline	0.2	0.14	0.18	0.03	0.12	6.40E-10
12.5% averse	0.18	0.14	0.15	0.04	0.13	1.87E-08
17.5% averse	0.19	0.14	0.18	0.03	0.13	4.14E-10
22.5% averse	0.2	0.14	0.19	0.04	0.15	1.85E-10
27.5% averse	0.2	0.14	0.18	0.02	0.11	3.65E-10
32.5% averse	0.2	0.14	0.18	0.03	0.12	8.75E-10
37.5% averse	0.2	0.14	0.19	0.03	0.13	2.34E-10

Summary statistics of p-values and R-squares of the linear regression models (trends) of disease incidence vs. time. For each scenario, 800 regression models were fit.

trend compared to the observed one. This means that the ABM parameterization tends to create dynamics of disease spread with overall lower incidence across time than what occurred in reality. The graphs in **Figure 6** display the time series of PEDv incidence for the observation data and for the scenario averages, calculated across the 800 Monte Carlo runs, along with their trends. Our outputs demonstrate that the mechanisms and parameterization of the ABM are capable of reproducing decreasing PEDv incidence through time thanks to the dynamics of human behavior where agents could respond to PEDv presence by increasing biosecurity. In other words, the human behavioral assumptions built into our ABM influencing biosecurity and disease transmission probabilities, allowed the realizations of negative incidence trends. Furthermore, the higher propensity to increase biosecurity assigned to risk averse agents did result in lower incidence when there was a sufficient number of risk averse agents in the population. Despite the fact that most of the simulations missed the observed initial high peak of incidence, the shaded areas displaying the averaged Monte Carlo outputs plus and minus one standard deviation demonstrate that the ABM did realize disease outbreaks with high peaks of incidence.

DISCUSSION

The epidemiological data on PEDv available for the period of June 1st, 2014 to February 25th, 2018 shows a decreasing trend in PEDv incidence. Because the characteristic pathways of infection of the virus have not changed over time, we deduced that something has been changing in the hog production system that has improved the control of the virus. Both the literature and collaborating stakeholders refer to human behaviors with respect to both in compliance with and investment in biosecurity as critical for disease-protection management. This implies a key role of humans in the processes of controlling virus transmission. To better understand how changes in behavioral patterns could reflect changes in PEDv incidence, we developed an agent-based model (ABM) able to examine the role of human risk attitude to PEDv incidence within a simulated production system. Our model outputs reproduced a significant decrease in PEDv incidence through time. An important finding from our scenario analysis was that the average decreasing trend is significantly affected by the model's initial state, defining the proportion of the producer agents assigned to two risk categories, risk averse and risk tolerant. An increase as small as 10% more risk averse producer agents resulted in a 19% decrease in the median total PEDv incidence, which is equivalent to 36 fewer PEDv cases over the course of the analysis period (~4 years). To observe a significantly steeper decrease in incidence requires that more than 37.5% of the population be in the risk averse category. The implication is that biosecurity adoption and influencing factors of adoption (for example risk attitude) are a critical consideration when creating strategic plans or policies for disease control. Our modeling analysis reinforces the message found not only in field-specific papers but also in general papers such as in (42) who calls for developing more effective approaches for integrating social dynamics of epidemics to build more realistic models.

PEDv incidence data are highly variable and reflect the complex social-ecological structure of the swine industry. While the Monte Carlo results capture much of the system variability, different parameter sets appear to more closely align with the observed PEDv data (**Figures 3–6**), i.e., the initial conditions allowed us to calculate the fraction of simulation runs whose patterns are statistically close to the recorded incidence patterns. An interesting finding is that a producer-agent population with only 12.5% agents in the risk averse category resulted in statistical indicators where the median is closer to the observed value. In considering potential adjustments for our model, this result suggests to use the risk-attitude distribution from 12.5% averse scenario as a model set-up for realizations closer to the observed PEDv pattern.

An aspect of complexity present in the observed data is their variability at several time scales including weekly, seasonal, and inter-annual variability. The inter-annual variability for example is visible in the timing of the observed incidence peaks (**Figure 6** top panel, example: the 2015–2016 winter peak occurred earlier than in 2014–2015). Our ABM uses a sinusoidal function calibrated to peak in January and therefore produces incidence oscillations that are more regular with time. A variety of reasons can be postulated to explain the complex variability in the observations including weather variability, changes in production components and/or routes and stochastic factors affecting disease spread. Our model simulates a closed production system where all the hog and feed movements are bounded within the region. Even if designed around the North Carolina configuration of production premises, the model does not include the complex network system that extends beyond the state boundary into other U.S. states. These out-of-state movements add potential for disease transmission and may contribute to the higher observed incidence compared to the averaged simulated one.

Human behavior and decision making represent a challenge in the animal production industry because of their complex interconnectedness with protection from disease (18, 19, 23, 43, 44). By weaving human behavioral components into epidemiological processes, our ABM is a unique tool for evaluating the effects and efficacy of disease control strategies compared to more traditional epidemiological models that lack social dynamics. Our ABM was equipped with two behavioral

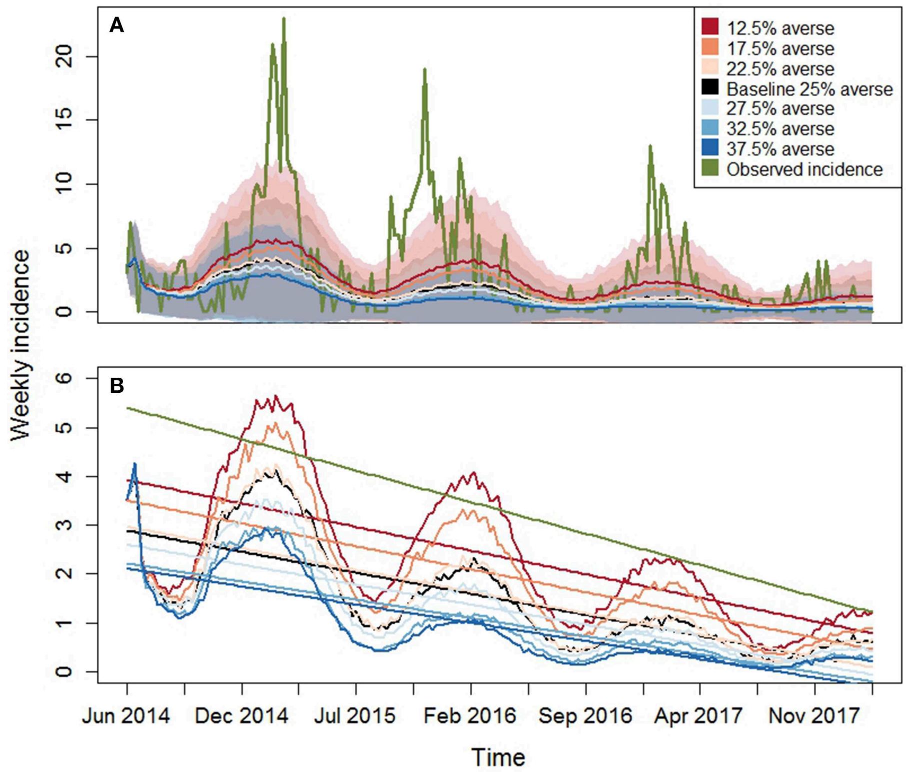

FIGURE 6 | Model results for PEDv incidence for the seven risk attitude scenarios (**Table 1**). Observed PEDv Incidence and its linear trend are overlaid in green. **(A)** Time series of averaged simulated PEDv incidence (lines) and one-standard-deviation bands derived from the 800 Monte Carlo runs for each scenario. **(B)** Zoom on simulated outputs with overlaid trends obtained from averaged linear regressions on each simulation run. The green line represents the linear trend of the observed data. The other colors are the same as described in the legend of the top panel.

processes that act in opposition: (1) responsiveness to regional disease incidence with consequent increase in biosecurity and (2) psychological distancing with consequent decrease in biosecurity as time increases since an infection. Model calibration provided the appropriate tension between the two processes to match the observed decreasing trend in PEDv incidence. With these two behavioral processes we were able to capture important features of the PEDv dynamics as shown in our results. We recognize however that there is a variety of interplaying socio-psychological factors that influence decisions, as skillfully illustrated by Mankad (18). Yet our ABM is a simplified but progressive effort toward more realistic representation of epidemics.

PEDv is highly contagious and lethal in piglets that has resulted in substantial losses for the North America's swine industry. All industry actors are aware of the devastating consequences of disease incursion. The regular reemergence of PEDv indicates that there is still work to do on the epidemiology and microbiology of the virus but also on the role of humans, which necessitates the investigation of practices carried out in the industry and behaviors that allow the virus to survive and become active. Intensive research efforts in the past 5 years have brought new information about the viability of the virus (5, 7, 12, 30, 40, 45–47), and vaccines have been researched in various countries around the world. Vaccine efficacy has shown to be low (48) although a recent study had promising results with a new vaccine that was immunogenic and effective in growing pigs (49). Prevention of the virus therefore relies on good biosecurity practices with active participation of producers and all industry stakeholders in this complex supply chain network. Crucial for biosecurity to work is the proper training of staff and a culture of compliance with the protocols.

Human risk attitude is a driver when examining the role of human behavior as a factor in disease transmission. Our study suggests that shifting producer attitudes toward risk aversion is beneficial for the whole production system because it will result in reduced disease incidence. In balancing cost and benefits of biosecurity, our modeling outputs show that an engaged effort from the population of producers toward more risk averse, biosecure behaviors (e.g., readiness to enhance biosecurity and limiting psychological distancing) is effective in the control and reduction of PEDv spread. Our study points at the substantial opportunity provided by shifting behavior; however, from a production system perspective, altering a substantial proportion of a population's behavior represents a significant challenge. Yet, significant progress has been shown in other industries, for example when we alter choice architecture and provide behavioral nudges (25, 50).

Here we demonstrated the need to better understand the cognitive processes underlying decision-making about biosecurity, and highlight possible realizations of the impact of changing behavior on the spread of disease in the swine industry. However, in this research we coded biosecurity investment decisions based on the risk of acquiring a disease. Obviously, disease risk is an important factor when considering biosecurity, but it is not the only factor. A complex array of factors exists that influence biosecurity decisions that differ by individual and further depend upon the objectives of the organization, regional policies, logistical factors, and the array of behaviors by other actors in the swine network (e.g., feed mills, truck drivers, veterinarians, slaughter plants, processors, auction houses, etc.). Yet, research has shown that risk attitude can be an important decision-making factor. Like all models, our "model is wrong, but hopefully it is useful" (attributed to George Box 1976) because it provides a quantitative approximation for how human behavior and decisions can influence the spread of disease.

CONCLUSION

The onset of PEDv in the U.S. hog industry was a singular experience for all stakeholders because of its high infectivity and rapid spread. Data show however that in 4 years, PEDv's potent spread appeared constrained with overall incidence reduced. Social dimensions can play a significant role in the biosecurity decisions of swine producers. We geared our epidemiological model with human behavioral processes connected to biosecurity and disease, and demonstrated the opportunity and impact associated with changing biosecurity behavior on PEDv incidence or, with a more positive spin, a healthier animal production systems. If on one side, targeted interventions to critical nodes of a production system may prove important to inhibit disease "super-spreaders," on the other, our study shows that shifts in the overall industry toward a more risk averse culture can yield more biosecure facilities along with consistent and long-term industry-wide protection from disease.

AUTHOR CONTRIBUTIONS

GB, SW, EC, and SCM assisted with design and conceptualization of the agent-based model. EC helped with data collection. GB, SCM, EC, and SMM worked on data analysis. Project funding was generated with the help of JS, SCM, CK, and AZ. Experiments were conducted by GB and EC. Software development was primarily led by GB, SW, and EC. Initial manuscript drafts were created by GB. Subsequent manuscript editing was completed by all authors.

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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.2019.00196/full#supplementary-material

REFERENCES

1. Paarlberg PL. *Updated Estimated Economic Welfare Impacts of Porcine Epidemic Diarrhea Virus (PEDV)*. West Lafayette, IN: Department of Agricultural Economics, Purdue University (2014).
2. Pudenz C, Schulz L, Tonsor G. *Biosecurity and Health Management by U.S. Pork Producers-2017 Survey Summary*. Ames, IA: Iowa State University Extension and Outreach (2017).
3. Geiger JO, Connor JF. *Porcine Epidemic Diarrhea, Diagnosis and Elimination*. (2013). Available online at: https://www.aasv.org/aasv%20website/Resources/Diseases/PED/13-05-29PEDWhitePaper.pdf (accessed 29 May, 2013).
4. Stevenson GW, Hoang H, Schwartz KJ, Burrough ER, Sun D, Madson D, et al. Emergence of porcine epidemic diarrhea virus in the United States: clinical signs, lesions, and viral genomic sequences. *J Vet Diagn Investig.* (2013) 25:649–54. doi: 10.1177/1040638713501675
5. Alonso C, Goede DP, Morrison RB, Davies PR, Rovira A, Marthaler DG, et al. Evidence of infectivity of airborne porcine epidemic diarrhea virus and detection of airborne viral RNA at long distances from infected herds. *Vet Res.* (2014) 45:73. doi: 10.1186/s13567-014-0073-z
6. Dee S, Clement T, Schelkopf A, Nerem J, Knudsen D, Christopher-Hennings J, et al. An evaluation of contaminated complete feed as a vehicle for porcine epidemic diarrhea virus infection of naïve pigs following consumption via natural feeding behavior: proof of concept. *BMC Vet Res.* (2014) 10:176. doi: 10.1186/s12917-014-0176-9
7. Lowe J, Gauger P, Harmon K, Zhang J, Connor J, Yeske P, et al. Role of transportation in spread of porcine epidemic diarrhea virus infection, United States. *Emerging Infect Dis.* (2014) 20:872–4. doi: 10.3201/eid2005.131628
8. Bowman AS, Krogwold RA, Price T, Davis M, Moeller SJ. Investigating the introduction of porcine epidemic diarrhea virus into an Ohio swine operation. *BMC Vet Res.* (2015) 11:38. doi: 10.1186/s12917-015-0348-2
9. Dee S, Neill C, Clement T, Singrey A, Christopher-Hennings J, Nelson E. An evaluation of porcine epidemic diarrhea virus survival in individual feed ingredients in the presence or absence of a liquid antimicrobial. *Porcine Health Manage.* (2015) 1:9. doi: 10.1186/s40813-015-0003-0
10. Alvarez J, Goede D, Morrison R, Perez A. Spatial and temporal epidemiology of porcine epidemic diarrhea (PED) in the Midwest and Southeast regions of the United States. *Prev Vet Med.* (2016) 123:155–60. doi: 10.1016/j.prevetmed.2015.11.003
11. Lachapelle V, Letellier A, Fravalo P, Brassard J, L'Homme Y. Dynamics of virus distribution in a defined swine production network using enteric viruses as molecular markers. *Appl Environ Microbiol.* (2017) 83:e03187–16. doi: 10.1128/AEM.03187-16
12. Kim Y, Krishna V, Torremorell M, Goyal S, Cheeran M. Stability of porcine epidemic diarrhea virus on fomite materials at different temperatures. *Vet Sci.* (2018) 5:21. doi: 10.3390/vetsci5010021
13. Murai K, Moriguchi S, Hayama Y, Kobayashi S, Miyazaki A, Tsutsui T, et al. Mathematical modeling of porcine epidemic diarrhea virus dynamics within a

farrow-to-finish swine farm to investigate the effects of control measures. *Prev Vet Med.* (2018) 149:115–24. doi: 10.1016/j.prevetmed.2017.11.019

14. Niederwerder MC, Hesse RA. Swine enteric coronavirus disease: a review of 4 years with porcine epidemic diarrhoea virus and porcine deltacoronavirus in the United States and Canada. *Transbound Emerg Dis.* (2018) 65:660–75. doi: 10.1111/tbed.12823
15. Zentkovich MM, Nelson SW, Stull JW, Nolting JM, Bowman AS. Inactivation of porcine epidemic diarrhea virus using heated water. *Vet Anim Sci.* (2016) 1–2:1–3. doi: 10.1016/j.vas.2016.09.001
16. Trudeau MP, Verma H, Urriola PE, Sampedro F, Shurson GC, Goyal SM. Survival of porcine epidemic diarrhea virus (PEDV) in thermally treated feed ingredients and on surfaces. *Porc Health Manag.* (2017) 3:17–17. doi: 10.1186/s40813-017-0064-3
17. Gebhardt JT, Cochrane RA, Woodworth JC, Jones CK, Niederwerder MC, Muckey MB, et al. Evaluation of the effects of flushing feed manufacturing equipment with chemically treated rice hulls on porcine epidemic diarrhea virus cross-contamination during feed manufacturing. *J Anim Sci.* (2018) 96:4149–58. doi: 10.1093/jas/sky295
18. Mankad A. Psychological influences on biosecurity control and farmer decision-making. *Rev Agron Sust Dev.* (2016) 36:40. doi: 10.1007/s13593-016-0375-9
19. Hidano A, Enticott G, Christley RM, Gates MC. Modeling dynamic human behavioral changes in animal disease models: challenges and opportunities for addressing bias. *Front Vet Sci.* (2018) 5:137. doi: 10.3389/fvets.2018.00137
20. Ritter C, Jansen J, Roche S, Kelton DF, Adams CL, Orsel K, et al. Invited review: determinants of farmers' adoption of management-based strategies for infectious disease prevention and control. *J Dairy Sci.* (2017) 100:3329–47. doi: 10.3168/jds.2016-11977
21. Edwards-Jones G. Modelling farmer decision-making: concepts, progress, and challenges. *Anim Sci.* (2007) 82:783–90. doi: 10.1017/ASC2006112
22. Merrill SC, Koliba CJ, Moegenburg SM, Zia A, Parker J, Sellnow T, et al. Decision-making in livestock biosecurity practices amidst environmental and social uncertainty: evidence from an experimental game. *PLoS ONE.* (2019) 14:e0214500. doi: 10.1371/journal.pone.0214500
23. Casal J, Manuel A, Mateu E, Martin M. Biosecurity measures on swine farms in Spain: perceptions by farmers and their relationship to current on-farm measures. *Prev Vet Med.* (2007) 82:138–50. doi: 10.1016/j.prevetmed.2007.05.012
24. Jin Y, Elbakidze L, McCarl BA. Risk assessment and management of animal disease related biosecurity. *Int J Risk Assess Manag.* (2009) 12:186–203 doi: 10.1504/IJRAM.2009.025918
25. Thaler RH, Sunstein CR, Balz JP. Choice Architecture. In: Shafir E, editor. *The Behavioral Foundations of Public Policy*. Princeton, NJ: Princeton University Press (2014). p. 428–39.
26. Funk S, Bansal S, Bauch CT, Eames KTD, Edmunds WJ, Galvani AP, et al. Nine challenges in incorporating the dynamics of behaviour in infectious diseases models. *Epidemics.* (2015) 10:21–5. doi: 10.1016/j.epidem.2014.09.005
27. Beam A, Goede D, Fox A, McCool MJ, Wall G, Haley C, et al. A porcine epidemic diarrhea virus outbreak in one geographic region of the united states: descriptive epidemiology and investigation of the possibility of airborne virus spread. *PLoS ONE.* (2015) 10:e0144818. doi: 10.1371/journal.pone.0144818
28. O'Dea EB, Snelson H, Bansal S. Using heterogeneity in the population structure of U.S. swine farms to compare transmission models for porcine epidemic diarrhoea. *Sci Rep.* (2016) 6:22248. doi: 10.1038/srep22248
29. Dee S, Neill C, Singrey A, Clement T, Cochrane R, Jones C, et al. Modeling the transboundary risk of feed ingredients contaminated with porcine epidemic diarrhea virus. *BMC Vet Res.* (2016) 12:51. doi: 10.1186/s12917-016-0674-z
30. VanderWaal K, Perez A, Torremorrell M, Morrison RM, Craft M. Role of animal movement and indirect contact among farms in transmission of porcine epidemic diarrhea virus. *Epidemics.* (2018) 24:67–75. doi: 10.1016/j.epidem.2018.04.001
31. Verelst F, Willem L, Beutels P. Behavioural change models for infectious disease transmission: a systematic review (2010–2015). *J Royal Soc Interface.* (2016) 13:20160820. doi: 10.1098/rsif.2016.0820
32. Badham J, Chattoe-Brown E, Gilbert N, Chalabi Z, Kee F, Hunter RF. Developing agent-based models of complex health behaviour. *Health Place.* (2018) 54:170–7. doi: 10.1016/j.healthplace.2018.08.022
33. Smith ER, Conrey FR. Agent-based modeling: a new approach for theory building in social psychology. *Personal Soc Psychol Rev.* (2007) 11:87–104. doi: 10.1177/1088868306294789
34. Epstein JM. Modelling to contain pandemics. *Nature.* (2009) 460:687. doi: 10.1038/460687a
35. Bruch E, Atwell J. Agent-based models in empirical social research. *Sociol Methods Res.* (2015) 44:186–221. doi: 10.1177/004912411350 6405
36. Yi R, Gatchalian KM, Bickel WK. Discounting of past outcomes. *Exp Clin Psychopharmacol.* (2006) 14:311–7. doi: 10.1037/1064-1297.14.3.311
37. Wiltshire S, Zia A, Koliba C, Bucini G, Clark E, Merrill S, et al. Network metametrics: using evolutionary computation to identify effective indicators of epidemiological vulnerability in a livestock production system model. *J Artif Soc Soc Simul.* (2019) 22:8. doi: 10.18564/jasss.3991
38. Wiltshire SW. Using an agent-based model to evaluate the effect of producer specialization on the epidemiological resilience of livestock production networks. *PLoS ONE.* (2018) 13:e0194013. doi: 10.1371/journal.pone.0194013
39. Burdett CL, Kraus BR, Garza SJ, Miller RS, Bjork KE. Simulating the distribution of individual livestock farms and their populations in the united states: an example using domestic swine (sus scrofa domesticus) farms. *PLoS ONE.* (2015) 10:e0140338. doi: 10.1371/journal.pone.0140338
40. Tun HM, Cai Z, Khafipour E. Monitoring survivability and infectivity of porcine epidemic diarrhea virus (PEDv) in the infected on-farm earthen manure storages (EMS). *Front Microbiol.* (2016) 7:265. doi: 10.3389/fmicb.2016.00265
41. R Core Team. *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing (2016). Avaliable online at: https://www.R-project.org/
42. Ferguson, N. (2007). Capturing human behaviour. *Nature*. 446:733. doi: 10.1038/446733a
43. Brennan ML, Christley RM. Cattle producers' perceptions of biosecurity. *BMC Vet Res.* (2013) 9:71. doi: 10.1186/1746-6148-9-71
44. Dewey C, Bottoms K, Carter N. A qualitative study to identify potential biosecurity risks associated with feed delivery. *J Swine Health Product.* (2014) 22:232–43. Available online at: https://www.aasv.org/shap/issues/v22n5/v22n5p232.html
45. Kim Y, Yang M, Goyal SM, Cheeran MC-J, Torremorell M. Evaluation of biosecurity measures to prevent indirect transmission of porcine epidemic diarrhea virus. *BMC Vet Res.* (2017) 13:89. doi: 10.1186/s12917-017-1017-4
46. Schumacher LL, Huss AR, Cochrane RA, Stark CR, Woodworth JC, Bai J, et al. Characterizing the rapid spread of porcine epidemic diarrhea virus (PEDV) through an animal food manufacturing facility. *PLoS ONE.* (2017) 12:e0187309. doi: 10.1371/journal.pone.0187309
47. Vitosh-Sillman S, Loy JD, Brodersen B, Kelling C, Eskridge K, Millmier Schmidt A. Effectiveness of composting as a biosecure disposal method for porcine epidemic diarrhea virus (PEDV)-infected pig carcasses. *Porc Health Manag.* (2017) 3:22. doi: 10.1186/s40813-017-0068-z
48. Song D, Moon H, Kang B. Porcine epidemic diarrhea: a review of current epidemiology and available vaccines. *Clin Exp Vaccine Res.* (2015) 4:166–76. doi: 10.7774/cevr.2015.4.2.166
49. Lee SH, Yang D-K, Kim H-H, Cho I-S. Efficacy of inactivated variant porcine epidemic diarrhea virus vaccines in growing pigs. *Clin Exp Vaccine Res.* (2018) 7:61–9. doi: 10.7774/cevr.2018.7.1.61
50. Thaler RH, Sunstein CR. *Nudge: Improving Decisions About Health, Wealth, and Happiness*. New Haven, CT: Yale University Press (2008).

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Opportunities for Brucellosis Control in Mexico: Views Based on the Sustainable Livelihoods Perspective

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Caprine brucellosis is a main constraint for small-scale goat husbandry systems in the Global South, as it negatively affects production parameters and can be transmitted to humans. The aim of this manuscript is to point out opportunities for brucellosis control in a resource poor area. The present paper draws from previous research in two Mexican states, Jalisco and Michoacán, both within the Bajío region. Main opportunities for brucellosis control are discussed within the "Sustainable Livelihoods Perspective." Goat farming gives farmers a number of livelihoods benefits: food, cash, prestige, and a job. Goat farming is also a reason for some farmers to stay in their villages rather than to migrate to the US. This livelihood strategy, however, is threatened by brucellosis, which is endemic in the goat population of the region. Brucellosis control, however, offers an opportunity for small-scale goat farmers to enhance health and welfare. The socio-economic context is very important in planning a successful brucellosis control campaign. Control strategies should be planned considering the local goat farming husbandry and the views of the farmers.

Keywords: Bajío, disease control, livelihoods, "One health", smallholders, zoonosis, goats, participatory methods

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INTRODUCTION

Brucellosis is a common zoonotic disease worldwide (1). Despite the wealth of knowledge, including tools like vaccines and serological tests, brucellosis remains endemic in Mexico as in many other countries of the global South (2). Goats are the natural host of *Brucella melitensis*, which is considered to be the most virulent *Brucella* specie in humans. Caprine brucellosis is a great constraint for smallholder goat farming development and a threat for public health and for farmers' livelihoods (3). Although brucellosis is unlikely to be a fatal disease in humans, who are accidental hosts, it is a severe health condition, very debilitating, and disabling (4).

It causes high fever and may lead to complications, such as arthritis and spondylitis, abortion in pregnant women and orchitis in men (5, 6). Brucellosis infections are often not timely recognized as fever, an early symptom, is a clinical sign of many other infectious diseases. In developed countries, it can happen that physicians are not alert to suspect brucellosis in patients as brucellosis is not present in domestic livestock from many northern countries (7–9).

Disciplinary research with regard to brucellosis has been key for the control of brucellosis. Vaccines and serological testing are important technologies that have been used with great success in developed countries (10, 11). In the Global South, however, these technologies are not widely adopted by farmers and therefore brucellosis control is still ineffective. Smallholder farmers in the global South are embedded in complex context which is characterized first by the various purposes livestock husbandry has. First, keeping animals is a source of income, food, security, manure, prestige, and security among others. In addition livestock husbandry is often one of many other activities or strategies that farmers have. Second, strong governmental institutions are often lacking and third are prone to shocks, trends, and seasonality; which can be droughts, inflation, insecurity, and violence to mention some. Thus, strategies to improve livestock husbandry need to be in harmony with farmers' goals aiming to help them to better cope with a tough environment. The sustainable livelihoods framework can be an approach to capture the complexity of farmers livelihoods (12).

The aim of this paper is to explore feasible opportunities for brucellosis control in Mexico through the lens of the sustainable livelihoods perspectives. We argue that current control strategies for brucellosis in goats could have more impact if they are drawn from a liveslihoods perspective. This paper is organized as follows: as a background we first present a brief explanation of how brucellosis control is organized in Mexico and briefly show the current status of brucellosis in livestock control in Mexico and the incidence of human brucellosis in recent years. We then characterize the goat farming system and how goat farmers make a living. Finally an explanation of the linkages between goat husbandry and brucellosis endemicity is presented to show opportunities for brucellosis control based on farmers livelihoods.

BRUCELLOSIS IN MEXICO: POLICIES AND PROGRESS TO CONTROL IT

Brucellosis control in Mexico is based on a set of rules issued in 1995 (13). The "Norma Oficial Mexicana NOM−041-ZOO-1995" enlists the steps to control brucellosis. Three phases of brucellosis control are considered: (1) control, (2) eradication, and (3) free. Actions vary depending on the progress in a region as follows:

Control
Applied to a region with high seroprevalence (>3%). The core strategy is to vaccinate all ruminants.

Eradication
For a region with a low seroprevalence (<3%) the strategy focuses on test-and-cull of seropositive animals.

Free
A region and also individual farms can obtain a free status recognition if the herds of cattle and flocks of small ruminants have been seronegative in 3 consecutive years. The core strategy then is continuous surveillance.

Only three municipalities of the west northern state Sonora are free of brucellosis. Sixteen municipalities have reached the eradication phase. The latter belong to 13 states scattered in central Mexico, in the south-east, western coast, and one state in the north coast. All other municipalities are in control phase (14).

The campaign for eradication and control for brucellosis is decentralized; each state has a committee for animal production, health, and welfare. Committees are funded by public resources. For the control of brucellosis, committees receive resources from the federal government to pay for staff salaries, vaccines against brucellosis, and biological reagents; i.e., Rose Bengal test to run serological analysis. The way each committee administrates its resources varies largely. Some committees hire their own field staff for vaccination and surveillance while other committees provide inputs for freelance veterinarians. Freelance veterinarians will offer their services to farmers and charge for their services to farmers.

LIVELIHOODS AND GOAT HUSBANDRY

The sustainable livelihoods perspective is utilized to analyze how farmers make use of their capabilities, assets, and strategies to make a living and to cope with shocks, trends, and seasonality (12).

The five key capitals often considered in livelihoods perspectives are: (1) Natural capital; such as farmers' crop and grazing land. (2) Social capital; farmers' connections and working together patterns. (3) Financial capital; income, credits, and cash. (4) Human capital, people's health, age, gender, knowledge, and skills. (5) Physical capital, infrastructure, and the means to generate financial capitals such as goat flocks (15).

Within the livelihoods perspectives these five key capitals help people to withstand a vulnerability context where shocks, trends, and seasonality occur. A shock can be a disease outbreak, trends are for example, declining rural population and seasonality can refer to farming cycles; milking, lambing, cropping, harvesting, and others like, weather related cycles. Capitals are also the means by which people implement livelihoods strategies; these are for example, livestock husbandry, off-farm work, and cropping among others, resulting in outcomes such as more income, reduced vulnerability, and more sustainable natural resource based (15). Livestock is often considered a vital physical asset which can help people to be less vulnerable and even the means to step out of poverty (16).

We have used mixed methodology of qualitative and quantitative methods to characterize goat farmers livelihoods and caprine brucellosis status in the Mexican Bajío within the states of Michoacán and Jalisco (17). We have chosen this region because is a goat dairy basin area within the Bajío of Mexico (**Figure 1**).

The Bajío is located in west central Mexico and has been characterized since colonial times by the quality of the crop land. Main crops are maize, wheat, beans, and chickpeas by the Goat husbandry played a key role in farmers livelihoods. **Figure 2** shows a feedback system representation of goat husbandry. From a longitudinal survey with 46 farmers chosen by convenience we found that average number of dairy does in flock was 65. Does required human capital; this is farmers' care and work, in return farmers obtained animal protein from goats, i.e., milk and meat. The average milk yield was 0.80 liters per day per doe. Goat's milk was sold, which provided a weekly income.

Besides labor, a goat flock required inputs such as feed and veterinary drugs. Goats were integrated to the cropping system of the region and were herded to graze crop residues while their manure was a natural fertilizer. Having goats allowed people to work with others, farmers helped each other in their tasks

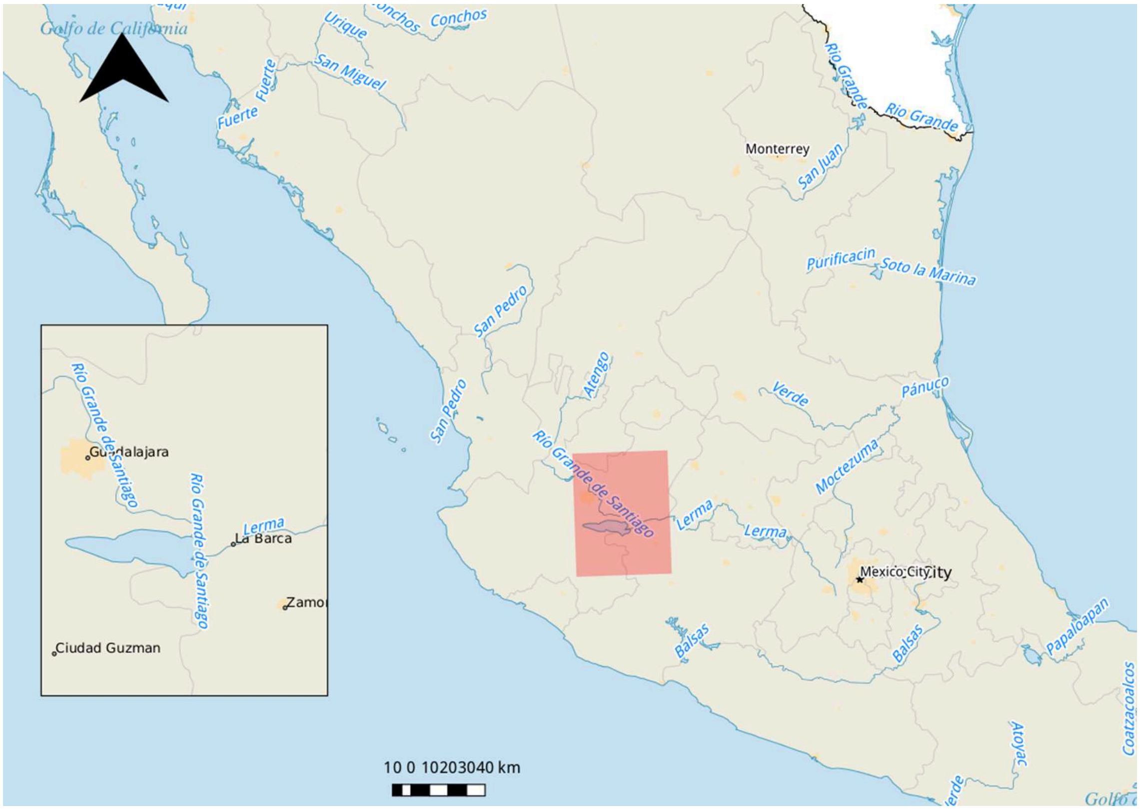

FIGURE 1 | Localization of the research area. Source: own elaboration.

by taking turns in grazing two or three flocks together. In addition goat kids were gifts to pay back for favors or services. Bajío farmers were often granted to herd their flocks to graze crop residues in neighbors' crop land. In return farmers made payment-in-kind with a goat kid (17). In general, goat farming popularity among resource-poor farmers of the region shows a revival contrasting with figures at national level where the number of goat farmers dropped by 40 between 1991 and 2007 (18, 19). Smallholder farmers of the Bajío are eager to keep goats for the following three reasons:

First, jobs scarcity; well-paid jobs in the region are scant and undocumented emigration to the USA has become riskier and tougher. A farmer said to us when we asked him why is that he became a goat farmer:

> "Here in this village you either have goats or you go to the US; I was once an immigrant. I did not like it, this why I am a goat farmer."

Farmers appreciate very much goat farming as it is a source of income. They said colloquially "it is better to herd than be herded" meaning that farmers are happier being their own boss rather than obeying someone else. Goat farming can be carried out by landless farmers.

Second, a growing demand for goat milk and cropping maize the main staple crop is less profitable. The demand for goat milk is triggered by the caramel industry. This industry monopolizes goat milk trade to make caramels sold in Mexico and in the US.

Third, the relative low cost of feeding goats. In the Bajío region of Michoacán and Jalisco goat husbandry is pre-dominantly a pastoral activity. Goats are herded to graze crops residues in the valleys during the dry season and native vegetation in the hills and mountains during the rainy season.

Besides goat farming other livelihood strategies are utilized by households to make a living, such as cropping, other livestock rearing (cattle, poultry, pigs, and sheep), off-farm work, and remittances (3).

BRUCELLOSIS CONTROL: OPPORTUNITIES FOR SUSTAINABLE LIVELIHOODS

A drawback of goat husbandry in the area is brucellosis endemicity in the goat population. Our serological survey in 1,768 goats showed a high brucellosis apparent prevalence in goats: 11–38% depending on the region (20). Not surprisingly, villagers avoid goat milk in their diet. Drinking goat milk causes fever farmers said. Moreover, brucellosis has afflicted farmers badly, according to the testimonies of two farmers one had a spinal involvement due to brucellosis and the other epididymo-orchitis.

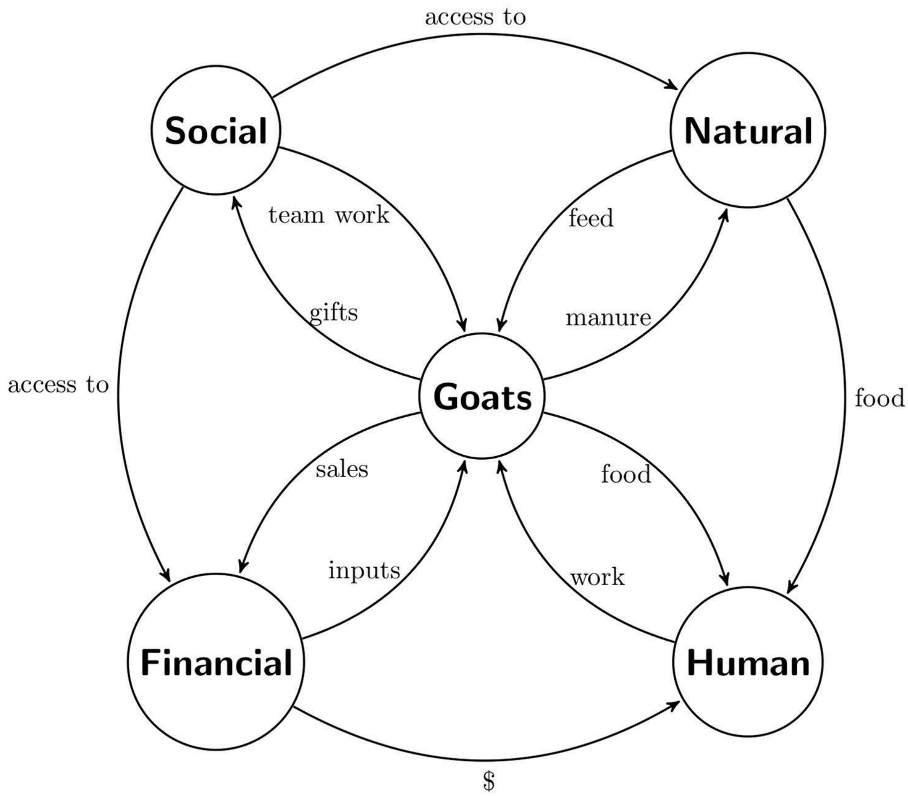

FIGURE 2 | Flow chart of livelihood assets around goats. Source: own elaboration.

Brucellosis infections in humans are shocks, which are part of the vulnerability context and have a negative effect on the human capital. Likewise brucellosis outbreaks in goat flocks diminishes farmers physical capital quality due to abortion, mastitis, infertility, and goat kid mortality (21). Hence, brucellosis control is an opportunity to reduce farmers' vulnerability, increase their income and well-being, improve food security, and provide a better natural resource base. We do not need to reinvent the wheel, enough technologies have been out for a long time. The key is then to understand farmers' limitations to adopt an effective brucellosis control strategy.

VACCINATION: EFFECTS AND COSTS

Brucellosis in livestock can be controlled with the use of vaccines. The efficacy of vaccination in small-ruminants is well-documented (21–24). We found significant difference in the seroprevalence of goats depending on difference in vaccination: 38% in Jalisco (poorly vaccinated) and 11% in Michoacán (intensively vaccinated) (20).

It is generally accepted that vaccination is inexpensive, but this is not so for Mexican farmers. In Jalisco farmers willing to vaccinate their flocks were charged 10 Mexican pesos per goat [in 2008 the exchange rate of a Mexican peso (MX) was 0.08 US (25)]. While this price per goat vaccinated might be seen as inexpensive, it was not to the farmers who were used to vaccinate goats against other diseases, and these costs were about nine times cheaper compared to brucellosis vaccination. Furthermore, during the field work we noticed that freelance veterinarians in Jalisco rarely visited farmers to offer the vaccination and once a veterinarian vaccinated goats at the wrong time of the year; goats were pregnant when vaccinated, resulting in an abortion storm in some of the flocks [(15), p. 92].

So farmers can be reluctant to invest in vaccination being afraid for potential errors at vaccine application and because the unawareness of the benefits of brucellosis control can have through vaccination.

We have simulated the economic benefits of different control strategies for various scenarios (26). The simulation was run through a series of epidemiological and economic models. Our models have shown that a regional caprine brucellosis vaccination campaign can be economically rewarding for the goat sector (26). The cost/benefit ratio of vaccination was 3.8 MX and the net present value was 3.2 MX. We could not calculate the benefits on human health, to our knowledge this has not been evaluated yet in Mexico. Roth et al. (27) showed that the economic benefits of vaccination of cattle and sheep in Mongolia were substantial; three times higher than the cost of the intervention for the whole country in a 10 year-period (about 18 million USD), taking the impact on human health into account.

According to our models in Oseguera Montiel et al. (26) vaccination with Rev 1 does not eradicate brucellosis though it will reduce its prevalence. In brucellosis endemic goat populations, brucellosis vaccination on its own can lower the seroprevalence by two thirds in a 10 year-period. To lower the prevalence below 3%, which is the eradication phase according to the Mexican law, will need a test-and-cull strategy. Caprine brucellosis eradication, through test-and-cull is considered to be hard to achieve and is most unlikely to happen in developing countries. A possibility to apply a test-and-cull strategy could be to add value to goat milk by entering a different market through a value chain. Our research showed that test-and-cull approach becomes feasible in economic terms if farmers could sell their milk for a three times higher price (26).

Currently the goat milk processing industry does not pay more for milk coming from brucellosis free flocks, probably because goat milk is used for caramels and they see no risk of brucellosis for consumers as the pathogen does not survive the production process. Farmers' opportunity then is by negating the dairy industry, e.g., brucellosis control could offer an opportunity to create a new market. A potential marketing possibility could be to offer goat products directly to consumers by-passing middlemen, retailers, and the big dairy industry. Farmers in the study site are close to good potential markets, such as Guadalajara metropolis with 4 million people about 150 km from the villages. Farmers have to get involved in local initiatives promoting fair trade of their products which need to be of good quality and free of pathogens, especially *Brucella* spp.

PARTICIPATORY BRUCELLOSIS CONTROL STRATEGY

It seems that little attention is given to the problems farmers in the global South encounter to implement brucellosis control strategies. Engagement of farmers in designing the control strategy is very much needed. Thus, a good understanding of farmers' practices, knowledge, interests, beliefs, and experiences is needed (28). We propose a strategy that takes into account the latter aspects.

First, help farmers to reach better markets. A positive feedback loop has to be sought, i.e., better quality and safe milk resulting in better cash returns to farmers. Farmers' main concern is the milk price, which does not keep up with the inflation. If they could get a better price for their milk when they have a brucellosis free flock, surely they will make the efforts to reach that status brucellosis away from their flocks.

Second, recognize farmers' knowledge and experience to gain their support. Various stakeholders such as milk buyers and state employees of the agricultural ministry (veterinarians, extensionists) showed low esteem of farmers and are arguing their lack of knowledge (29). Ethnographic methods (e.g., participatory observations and in-depth interviews) have shown, however, that farmers have a wealth of knowledge of the agro-ecology of the region, goat diseases, treatments, disease prevention, cropping, and economics (3). Farmers' knowledge explains partly why goat husbandry has persisted for almost 500 years and farmers have adapted production goals over time. And their knowledge will be useful for the design of brucellosis control strategies which are suited to farmers' socio-economic situation and agro-ecological context.

Third, Compensate farmers for their loss if a test-and-cull strategy. Financial support has been key for the success of brucellosis control campaigns in European countries (30). A proper test-and-cull strategy will bring down the prevalence more quickly. But test-and-cull will be very difficult to implement when farmers have to bear the costs on their own or when milk prices do not allow investment in test-and-cull.

Fourth, Make farmers more aware of all aspects related to brucellosis. While farmers have a wealth of knowledge on goat husbandry and some diseases including brucellosis there are some knowledge gaps to tackle. Especially farmers should be better informed about the implications of brucellosis in goats and ways to prevent infections in animals and humans. Broadcasting to inform farmers about brucellosis is an option, but there is a range of other possibilities. Smits (23) suggested the use of text messages in mobile phones, another possibility is to include some entertaining lectures about brucellosis for children in rural schools.

Fifth, Farmers could make use of their milk for their own use if they can boil their milk to minimize risks of brucellosis infection.

Sixth, A regional approach is needed to effectively control brucellosis. *Brucella* pathogens can spread beyond administrative borders (23). Brucellosis control in Mexico is organized within the boundaries of states. Direct and indirect transmission of brucellosis among goats of more than one state is possible and very likely as goats are traded between states or graze in border areas and in territories of two states alike.

CONCLUSIONS

In developing countries such as Mexico, caprine brucellosis is a great constraint for smallholder goat farming development and a threat for public health and especially for farmers' livelihoods. Brucellosis control has proven to be complex, and goes beyond veterinary sciences. By an understanding of farmers assets, livelihoods strategies, and their environment a livelihoods perspective approach helps to understand how farmers can benefit when they implement brucellosis control strategies.

AUTHOR CONTRIBUTIONS

The manuscript summarizes DO's Ph.D. dissertation, which was supervised by AvdZ, HU, and KF.

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REFERENCES

1. Pappas G, Papadimitriou P, Akritidis N, Christou L, Tsianos E. The new global map of human brucellosis. *Lancet Infect Dis*. (2006) 6:91–9. doi: 10.1016/S1473-3099(06)70382-6
2. OIE. *World Animal Health Information Database (Wahid) Interface*. (2018). Available online at: http://www.oie.int/wahis_2/public/wahid.php/Wahidhome/Home (accessed October 31, 2018).
3. Oseguera Montiel D, Keilbach Baer N, van der Zijpp A, Sato C, Udo H. It is better to herd than be herded.' Making a living with goats in the Bajío region, Mexico. *Pastoralism*. (2014) 4:1–18. doi: 10.1186/s13570-014-0009-2
4. Franco M, Mulder M, Gilman R, Smits H. Human brucellosis. *Lancet Infect Dis*. (2007) 7:775–86. doi: 10.1016/S1473-3099(07)70286-4
5. Pappas G, Akritidis N, Bosilkovski M, Tsianos E. Brucellosis. *New Engl J Med*. (2005) 353:1071–2. doi: 10.1056/NEJMc051799
6. Corbel M. *Brucellosis in Humans and Animals*. Geneva: World Health Organization (2006). p. 89.
7. Dalmak S, Erek E, Altiparmak M, Ulku U. A porter with pain in his neck. *Lancet*. (1996) 348:444. doi: 10.1016/S0140-6736(96)04123-2
8. Ben-Ami H, Behar DM, Fischer D, Edoute Y. Talking to the patient. *Lancet*. (2000) 356:1076. doi: 10.1016/S0140-6736(00)02732-X
9. Al Dahouk S, Nöckler K, Hensel A, Tomaso H, Scholz H, Hagen R, et al. Human brucellosis in a nonendemic country: a report from Germany, 2002 and 2003. *Eur J Clin Microbiol*. (2005) 24:450–6. doi: 10.1007/s10096-005-1349-z
10. Godfroid J, Scholz HC, Barbier T, Nicolas C, Letesson JJ, Wattiau P, et al. Brucellosis at the animal/ecosystem/human interface at the beginning of the 21st century. *Prev Vet Med*. (2011) 102:118–31. doi: 10.1016/j.prevetmed.2011.04.007
11. Blasco JM, A review of the use of *B. melitensis* Rev 1 vaccine in adult sheep and goats. *Prev Vet Med*. (1997) 31:275–83. doi: 10.1016/S0167-5877(96)01110-5
12. Scoones I. Livelihoods perspectives and rural development. *Peasant Stud*. (2009) 36:171–96. doi: 10.1080/03066150902820503
13. SAGAR. *Norma Oficial Mexicana NOM-041-ZOO-1995*, *Campaña Nacional Contra la Brucelosis en los Animales*. (1996). Available online at: https://www.gob.mx/cms/uploads/attachment/file/106184/NOM-041-ZOO-1995.pdf (accessed June 6, 2018).
14. SENASICA. *Campaña Nacional Contra la Eradicación de la Brucelosis*. (2018). Available online at: https://www.gob.mx/senasica/documentos/situacion-actual-del-control-de-la-brucelosis-en-mexico (accessed June 6, 2018).
15. Scoones I. *Sustainable Rural Livelihoods: A Framework for Analysis*. IDS Discussion Paper, Vol. 72 (1998) Brighton: IDS. Available online at: https://opendocs.ids.ac.uk/opendocs/ (accessed June 2019).
16. Kristjanson P, Krishna A, Radeny M, Kuan J, Quilca G, Sanchez-Urrelo A, et al. Poverty dynamics and the role of livestock in the Peruvian Andes. *Agric Syst*. (2007) 94:294–308. doi: 10.1016/j.agsy.2006.09.009
17. Oseguera Montiel D. *Keeping Goats or going north?: enhancing livelihoods of smallholder goat farmers through brucellosis control in Mexico* (dissertation/Ph.D. thesis). Wageningen University WUR, Wageningen, Netherlands (2014). Available online at: https://library.wur.nl/WebQuery/wurpubs/fulltext/312105 (accessed May 2019).
18. INEGI. *Data From: Instituto Nacional de Estadística y Geografía: Censo Agrícola*. Ganadero y Forestall (1991).
19. INEGI. *Data From: Instituto Nacional de Estadística y Geografía: Censo Agrícola*, Ganadero y Forestall (2007).
20. Oseguera Montiel D, Frankena K, Udo H, Keilbach Baer M, van der Zijpp A. Prevalence and risk factors for brucellosis in goats in areas of Mexico with and without brucellosis control campaign. *Trop Anim Health Prod*. (2013) 45:1383–9. doi: 10.1007/s11250-013-0375-6
21. Blasco J. Control and eradication strategies for *Brucella melitensis* infection in sheep and goats. *Prilozi*. (2010) 31:145–65.
22. Minas A, Minas M, Stournara A, Tselepidis S. The "effects" of Rev-1 vaccination of sheep and goats on human brucellosis in Greece. *Prev Vet Med*. (2004) 64:41–7. doi: 10.1016/j.prevetmed.2004.03.007
23. Smits H. Brucellosis in pastoral and confined livestock: prevention and vaccination. *Rev Sci Tech Off Int Epiz*. (2013) 32:219–28. doi: 10.20506/rst.32.1.2200
24. Ward D, Jackson R, Karomatullo H, Khakimov T, Kurbonov K, Amirbekov M, et al. Brucellosis control in Tajikistan using Rev 1 vaccine: change in seroprevalence in small ruminants from 2004 to 2009. *Vet Rec*. (2012) 170:100. doi: 10.1136/vr.100012
25. Banixco. (*Banco de México): Cotización de las Divisas que Conforman la Canasta del DEG y del DEG Respecto al Peso Mexicano*. (2008). Available online at: http://www.banxico.org.mx/ (accessed March 10, 2014).
26. Oseguera Montiel D, Mieghan B, Frankena K, Udo H, van der Zijpp A, Rushton J. Financial analysis of brucellosis control in small-scale goat farming in the Bajío region, Mexico. *Prev Vet Med*. (2015) 118:247–59. doi: 10.1016/j.prevetmed.2014.11.014
27. Roth F, Zinsstag J, Orkhon D, Chimed-Ochir G, Hutton G, Cosivi O, et al. Human health benefits from livestock vaccination for brucellosis: case study. *B World Health Organ*. (2003) 81:867–76. doi: 10.1590/S0042-96862003001200005
28. Dixon J, Banwell C, Ulijaszek S. When culture impacts health. In: Banwell C, Ulijaszek S, Dixon J, editors. *When Culture Impacts Health, Global Lessons for Effective Health Research*. London: Academic Press. (2013). p. 1–11. doi: 10.1016/B978-0-12-415921-1.00001-4
29. Oseguera Montiel D, Udo H, Frankena K, Zijpp A. 'la fiebre de malta': an interface of farmers and caprine brucellosis control policies in the Bajío region, Mexico. *Transbound Emerg Dis*. (2017) 64:171–84. doi: 10.1111/tbed.12359
30. Godfroid J, Al Dahouk S, Pappas G, Roth F, Matope G, Muma J, et al. A "One Health" surveillance and control of brucellosis in developing countries: moving away from improvisation. *Comp Immunol Microb*. (2013) 36:241–8. doi: 10.1016/j.cimid.2012.09.001

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Salmonella Control Programme of Pig Feeds Is Financially Beneficial in Finland

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To promote public health, Finland has adopted a stringent *Salmonella* control policy. However, the rationale of *Salmonella* control in pig feeds has been debated after a European Union (EU)-wide cost–benefit analysis, which provided mixed, country-specific results on whether control measures are economically beneficial. The aim of this study was to analyze the costs and benefits of current pig feed *Salmonella* control in Finland compared to a reduced control scenario. In addition, this study contributes to the literature by looking at the costs across stakeholder groups. The costs of preventive and monitoring measures were assessed, and a Monte Carlo model was developed to simulate costs caused by *Salmonella* contaminations along the pork supply chain (including feed importation, commercial feed manufacturing, feed transportation, mobile feed mixers, pig farms, slaughterhouses) and because of human salmonellosis originating from contaminated feed. The data were collected from official records and feed sector operators by surveys and interviews. The prevalence of *Salmonella* was obtained from a previously conducted risk assessment study. The total costs of pig feed *Salmonella* control were estimated on average to be €4.2–5.4 million per year (95% of simulated years between €2.1 and €9.1 million) for the current control scenario, and €33.8–34.8 million per year (95% €2.2 to €26.0 million) for the reduced control scenario. In the reduced control scenario, the monitoring and prevention costs were decreased down to €1.1–2.1 million, and the costs of *Salmonella* contaminations and human salmonellosis were up by €32.7 million when compared to the current control scenario. The results suggest that the current pig feed *Salmonella* control policy of Finland is economically profitable. It can reduce the costs caused by feed-related *Salmonella* contaminations on average by €29.4 million per year and provides public health benefits. Pig feed *Salmonella* control can support the effectiveness of the Finnish *Salmonella* Control Programme. The current pig feed *Salmonella* control policy benefits the consumers, while a substantial part of the costs are covered by feed operators. In order to increase the acceptability of current policy, greater attention to the allocation of financial responsibilities regarding the control measures may be required.

Keywords: ***Salmonella*, cost–benefit analysis, stochastic simulation, feed, contamination, risk, pig production**

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INTRODUCTION

Salmonella is a bacteria which can cause food-borne illness and negatively affect human health. It can be transferred between humans and nonhuman animals through contaminated food, drink, or the environment. Salmonellosis can incur economic losses to society due to increased health care costs, lost working days when people are ill, and mortality (1). Ao et al. (2) estimated that that 3.4 (range 2.1–6.5) million human cases of invasive non-typhoidal *Salmonella* disease occur globally each year. In the European Union member states, *Salmonella* is the most frequently reported pathogen in food (3). In 2013–2017, there were 19.7–21.0 human cases of salmonellosis per 100,000 population reported in the European Union (4). In Finland, ∼1,500 to 3,000 salmonellosis cases (26–58 cases per 100,000 population) have been reported each year (5), and about 2 out of 3 cases have been acquired from abroad. However, 70–90% of the actual cases have been estimated to remain unreported (6, 7).

The association between *Salmonella* contamination in feed and pigs is well known and epidemic feed-borne *Salmonella* outbreaks have occasionally been experienced. For instance, in 2003, a feed-borne outbreak of *Salmonella cubana* occurred in Sweden as a result of contamination in a feed plant. *Salmonella cubana* was detected in 49 of 77 pig farms having received possibly contaminated feed (8). A study published in 2008 (9) found that the prevalence of *Salmonella* spp. in slaughter pigs within the European Union (EU) was 10.3%. The estimates ranged by member state from 0% in Finland to 29% in Spain (9). The European Food Safety Authority (EFSA) (10) has estimated that around 10–20% of human *Salmonella* infections in EU may be attributable to the pig reservoir as a whole. Their quantitative microbial risk assessment analysis suggested that an 80 or 90% reduction in lymph node prevalence should result in a comparable reduction in the number of human cases attributable to pig meat products. EFSA (10) further suggests that by feeding only *Salmonella*-free feedstuffs, a reduction of 10–20% in high-prevalence member states and 60–70% in low-prevalence member states were foreseen in slaughter pig lymph node prevalence.

The literature shows several measures which can be used to mitigate the risk of *Salmonella* [see, e.g., review by Andres and Davies (11)]. Following appropriate biosecurity and feed-based interventions are among the most important measures to be taken. Preventive measures to control diseases can also lead to increased public trust toward the food system [see Clark et al. (12)]. To promote public health, Finland has adopted a stringent *Salmonella* control policy (13). The policy aims to decrease the occurrence of *Salmonella* across the food supply chain. The Finnish *Salmonella* Control Programme (FSCP) (14) covers the *Salmonella* surveillance and risk management measures for pigs, beef, and poultry, and the meat and eggs derived from these. At a national level, it aims to protect consumers through ensuring that <1% of animals and meat are contaminated with *Salmonella*. The program takes measures to reduce the risk of *Salmonella*-positive eggs or meat from reaching the market (15).

FSCP has been regarded to achieve high food safety targets of meat, milk, and egg food chains without high costs (16). FSCP has been regarded as economically profitable in the broiler meat supply chain (17–20), whereas the financial viability of *Salmonella* control in the pig sector or for feedstuffs has not been investigated. *Salmonella* control in pig feeds has been considered only by an EU-wide cost–benefit analysis (21), which evaluated five different *Salmonella* control options across the EU member states. These options varied depending on whether biosecurity at the farm, interventions based on high or low *Salmonella* prevalence, or transport and slaughterhouse measures were taken into account. In most cases, the benefits of the control options were lower than their costs. In the case of Finland, two options were financially viable [i.e., Net Present Value (NPV) was positive]: these included an establishment of a *Salmonella* control support unit and some increased sampling, as well as feed control measures either with or without transport and slaughterhouse measures. By contrast, an establishment of a *Salmonella* control support unit and some increased sampling with or without specific feed practices and farm-level biosecurity were not financially viable (21).

Studies provide conflicting evidence on whether feed-related interventions to control *Salmonella* are economically viable. While some studies have found that feed-related interventions can be financially beneficial either as such or as part of a wider program [e.g., Lawson et al. (22); Sundström et al. (23); Gavin et al. (24), FCC consortium (21)] other studies have found their costs higher than the benefits [e.g., Miller et al. (25); Goldbach et al. (26)].

While feeds, especially imported feed materials and feeds, are considered the most important source of *Salmonella* contaminations in animals, FSCP does not cover feedstuffs. However, the feed law does not allow feed in Finland to contain *Salmonella*. The feed operators must indemnify damage for a buyer of feed when the feed does not comply with the legal requirements, even when the incompliance is not caused by intent or negligence (Finnish Feed law, 86/2008). This principle is called strict liability. The prevalence of *Salmonella* in the Finnish pork chain is low [e.g., Maijala et al. (16)], and Jensen and Unnevehr (27) suggest that intervention costs increase when the desired level of pathogen approaches zero. Hence, is it relevant to investigate whether a control program is economically viable.

To comply with the regulations, feed operators apply voluntary and mandatory prevention and monitoring measures. This, together with the FCC consortium (21) results, has stimulated discussion on whether the current *Salmonella* control in pig feeds is cost-effective. The issue is scientifically and empirically interesting from several perspectives. Firstly, the overall financial viability of the pig feed *Salmonella* control is a pertinent issue. Secondly, another relevant question is how the costs and benefits of pig feed *Salmonella* control are distributed along the supply chain. This is important because if the costs of control are paid by different stakeholders rather than those who benefit from the measures, then some stakeholders may have inadequate economic incentives to promote stringent *Salmonella* control. Hence, this article contributes to the literature by studying the costs and benefits of the pig feed *Salmonella* control program across stakeholder groups. The data were collected from official records and from feed sector operators through surveys and interviews, conducted simultaneously with a risk assessment related to Finnish pork production. The epidemiological analysis was obtained from Rönnqvist et al. (28). The analysis takes into account the current *Salmonella* control, including statutory and voluntary measures, and compares the current situation with a reduced control scenario where current statutory *Salmonella* controls are applied in pig farms but not in full for the commercial feed manufacturers or feed or feed material importers.

MATERIALS AND METHODS

Salmonella Control Scenarios

Two scenarios to control *Salmonella* in pig feeds were compared. The first scenario corresponded to the current *Salmonella* control policy. The second scenario represented a reduced control policy. The main differences between the scenarios are represented in **Table 1**. In the reduced control scenario, fewer prevention and monitoring activities were targeted on imported feed, commercial feed manufacturing, feed storage, and mobile feed mixers in the reduced control than in the current control scenario. Some control measures were eliminated completely. If *Salmonella* was detected in feed, no actions were assumed to be taken to eliminate the pathogen from feed under the reduced control scenario. *Salmonella* contaminations in pigs or pork were assumed to be treated similarly in both scenarios.

While the price parameters were similar for both scenarios, there were differences in the parameters representing a prevalence of *Salmonella* and differences in whether the measures to monitor, prevent, or eradicate the bacteria were taken.

TABLE 1 | Measures applied in the current and in the reduced *Salmonella* control scenario, and the proportion of measures applied in the reduced control scenario (% of the current control policy costs which are incurred in the reduced control scenario)[a].

Salmonella control measures applied	Current control[a]	Reduced control
CONTROL AT IMPORT OF FEED AND FEED MATERIALS		
Official control measures	Yes	No (0%)
Self-monitoring, sampling	Yes	Reduced (50–90%)
Quarantine storage for high-risk feed	Yes	No (0%)
Eradication of *Salmonella* when detected	Yes	No (0%)
CONTROL AT COMMERCIAL FEED MANUFACTURING		
Treatment of feed, labor and materials[b]	Yes	Reduced (95%)
Maintaining appropriate hygiene	Yes	Yes (100%)
Pest control	Yes	Yes (100%)
Official control, sampling	Yes	No (0%)
Samples as self-control	Yes	Reduced (50–90%)
Self-monitoring and related documentation	Yes	Reduced (80%)
Eradication of *Salmonella* when detected	Yes	No (0%)
CONTROL AT MOBILE FEED MIXERS		
Treatment of feed	Yes	Reduced (50%)
Official control and sampling	Yes	No (0%)
Maintaining appropriate hygiene	Yes	Yes (100%)
Samples as self-control	Yes	Reduced (50–90%)
Self-monitoring and related documentation	Yes	Reduced (75%)
Eradication of *Salmonella* when detected	Yes	Reduced (0–100%)
CONTROL AT PIG FARMS		
Treatment of feed, acid treatment	Yes	Yes (100%)
Sampling	Yes	Yes (100%)
Maintaining appropriate hygiene	Yes	Yes (100%)
Eradication of *Salmonella* when detected	Yes	Yes, if detected in pigs (100%)
CONTROL AT SLAUGHTERHOUSE		
Extra measures if *Salmonella* is detected	Yes	Yes (100%)

[a]*In the current control policy scenario, all costs and measures were applied in full, which corresponds to 100% adoption rate in the reduced control scenario. Percentages in the reduced control scenario indicate which proportion of current control measures were applied, and hence, which proportion of costs were incurred when compared to the current control policy scenario.*
[b]*Heat treatment for production volumes more than 6 million kilograms, except liquid feed, vitamin, and mineral mixes.*

Computational Model

In order to assess the costs and benefits of pig feed *Salmonella* control in Finland, a model to simulate two types of costs for a given control scenario was developed. The costs were simulated on an annual basis. The first type of costs was costs associated with measures to prevent *Salmonella*. These included the cost of feed (heat) treatment and other measures to reduce the risk of *Salmonella* contamination, cleaning measures and pest control at different stages of the supply chain, statutory *Salmonella* sampling and official control checks made by authorities, and self-monitoring measures related to *Salmonella* control in commercial feed manufacturing. The second type of costs includes costs caused by realized *Salmonella* outbreaks and *Salmonella* arising from the contamination of pig feed. These costs included the costs of cleaning facilities where *Salmonella*-contaminated feed or pigs had been detected; the costs of treating contaminated feed with substances permitted to treat feed; losses due to idle production capacity at feed manufacturing, feed storage, or farms; costs due to *Salmonella* observed at slaughterhouse or in pork; costs due to human cases of salmonellosis; and tracing, product recalls, and labor and material input associated with these measures. The model considered these two types of costs to different stakeholders across the pork supply chain. The stakeholders included feed importers, commercial feed manufacturers, feed transporters, mobile feed mixers, pig farms, slaughterhouses, taxpayers (government), and consumers of pork. The benefits of effective *Salmonella* control were because of a reduced costs burden caused by realized *Salmonella* outbreaks and *Salmonella* arising from the contamination of pig feed (possibly leading to contamination of pigs or their environment).

The total annual costs (L) of control and prevention measures plus costs caused by *Salmonella* contaminations and human infections in each scenario were calculated as:

$$L = \sum_{h=1}^{H} P_h C_h + \sum_{i=1}^{24} \text{pa}'_i w_i Q_i + \sum_{j=1}^{9} \text{pa}''_j w_j Q_j + \sum_{k=1}^{14} \text{Pft}_k w_k Q_k d_k + \sum_{r=1}^{2} \text{Papp}_r w_r Q_r \theta_{1,r} + \sum_{m=1}^{4} P_m w_m Q_m \theta_m f d_m$$

where h refers to one of H cost items associated with preventive or monitoring costs; C_h refers to the total costs of item h, which is implemented fully or partly because of the goal of reducing *Salmonella* contamination; P_h is the proportion of prevention or monitoring measures' costs C_h that are associated with item h (i.e., if a measure is adopted for multiple reasons, this parameter indicates the contribution of the *Salmonella* control to the costs); i, j, k, and r are indices representing feed material (i), feed (j, k), or animal type (r), respectively, in connection with measures associated with the treatment of *Salmonella*-contaminated materials, animals, or humans; m refers to "severity" of human salmonellosis; pa'_i, pa''_j, Pft_k, Papp_r, and P_m represent the probability of *Salmonella* contamination or prevalence of *Salmonella* contamination occurring in i, j, k, r, or m; w is the cost caused by *Salmonella* contamination, or eradication of the pathogen, in i, j, r, k, or m; d_k is the proportion of true infections that will be detected; d_m is the proportion of each type of human infection; θ is the proportion of infections related to contamination in feed; and Q represents the quantity of pig feed materials, pig feed, pigs, or humans in the study population.

For feed materials at import and storage prior to feed manufacturing, pa'_i is the apparent prevalence (pa′) of *Salmonella* in feed material batches of 25 tons. For costs incurred at the industrial feed manufacturing stage, the apparent prevalence of *Salmonella* in manufactured compound or complete feed (pa''_j) was used. The occurrence of *Salmonella* contamination in pigs at the farm was modeled by using the probability of contamination (Pft_k), and the probabilities were specific to feeding type and animal (complete feeds for sows, piglets or fattening pigs, farm-made feeds plus complementary feeds for sows, piglets or fattening pigs). As this was the true prevalence, only the proportion d_k was considered to result in costly eradication measures.

The incidence of *Salmonella* in slaughter pigs was assigned with the observed prevalence of infections (Papp) represented by the prevalence in the lymph node samples, and the costs for infection (w_r) were relative to the number of pigs that were assumed to be influenced in the batch when a *Salmonella*-positive pig was detected. Finally, the annual prevalence of *Salmonella* infections in humans P_m was determined as a proportion of observed infections that could, according to the source attribution model, be linked to pig feeds. $P_m w_m Q_m \theta_m f d_m$ therefore represent the product of the prevalence in humans, size of the population in Finland, reporting factor $f = 11.5$ (21), proportion of infections associated with contamination in feed, and the proportion of infections associated with each type of human infection and cost w_m per infected person. The following sections characterize information used to parameterize the model.

Data

The information needed for the cost–benefit analysis was gathered from several sources, including the reports of the former Finnish Food Safety Authority (Evira), which has been called the Finnish Food Authority since January 1, 2019, the Finnish Farm Registry, and from a questionnaire that administered to the feed producers in Finland. The data were collected, and the simulations were carried out for 2013.

Data on the volume of pig meat and feed production, and the number of pig farms and pigs in Finland were based on the statistics of Luke (29) and Evira (30). The costs of preventive measures were defined for seven large commercial feed manufacturers, which produced in total 290,000 tons of commercial pig feed in 2013, as well as for 12 mobile feed mixers, which produced 33,000 tons of pig feed, and all the pig farms in Finland (∼1,600 farms in 2013). Commercial pig feed producers use the vast majority of the imported high-risk feed material listed in the Decree of the Ministry of Agriculture and Forestry on the pursuit of activities in the animal feed sector 548/2012. For this reason, the amount and cost of imported-high risk feed were estimated for these operators' production. The costs related to the time used for self-monitoring were assessed for pig farms that were registered as feed manufacturers (about 400 farms), as only these farms have a statutory requirement for self-monitoring.

The questionnaire was sent to nine feed mill operators, of which six responded. From the 432 pig farms that had reported feed manufacturing, 61 returned completed questionnaires and 53 other farms informed that they no longer had pork production. Only 2 mobile mixers out of 12 filled in the questionnaires. All the respondents did not answer all of the questions. Therefore, any missing operator information was added by using information sourced from other similar operators. Besides the questionnaire, complementary data were gathered by interviewing a mobile mixer and the staff of a feed mill. In addition to the survey and the interviews, cost and price information was collected from laboratories; service providers collaborating with the feed industry, such as pest control operators and warehouse operators; and experts in the feed industry.

Costs of Measures to Prevent *Salmonella*

Costs of preventive measures related to the import of feed and feed materials are caused by statutory *Salmonella* sampling (self-monitoring and official monitoring), possible fees by authorities, and quarantine storage for high-risk feed materials. The Finnish Food Authority (formerly Evira) is responsible for controlling *Salmonella* in feed. The control is based on legislation and described in the annual control plans. This covers the control of feed mills and other operators. The authorities carry out spot checks for the imported and non-imported feeds and control that feeds meet legal requirements.

In Finland, *Salmonella* samples are taken as official sampling from high-risk feed imported from outside the EU member states, and mainly as self-monitoring from the high-risk feed within the EU member states. More intensive monitoring is currently required for high-risk than non-high-risk feed materials. A Ministry of Agriculture and Forestry decree on the pursuit of activities in the animal feed sector (548/2012) states that high-risk feed materials listed in annex 3 of the decree (for example, soybean, rapeseed, and meals derived from these are considered as high-risk materials) and feed imported from outside the EU member states must be analyzed by official sampling, and by self-monitoring when importing from the member states. The amounts of imported high-risk feed materials used for pig feeds were evaluated based on the amount of manufactured pig feed per operator and the sample pig feed recipes obtained from feeding experts. The imported high-risk feed material attributed to pig feed production was about 55,000 tons in 2013. The additional warehouse capacity for the prolonged storing of feed at the harbor because of waiting for laboratory results for 4–6 days was included in the costing.

For the commercial feed manufacturers, such as feed mills, costs related to preventive measures consisted of *Salmonella* sampling, the treatment of feed, maintaining appropriate hygiene and cleanliness in the facility, self-monitoring, pest control, and official inspections, including the official *Salmonella* samples. Feed manufacturing was controlled by inspections and sampling based on the authorities' control plan, which focuses on those control points considered most risky. All the feed manufacturers were required to have a self-control system for a hazard analysis and critical control points (HACCP). Sampling and other measures are defined by the HACCP. Large feed mills were inspected annually. It was mandatory for all feed operators who produced more than 6 million kilograms of feed per year to treat their products with heat or acid to mitigate *Salmonella* in feed (Finnish feed law 86/2008, 23 §). Based on the survey, only two of the operators used other treatments than heat treatment.

Acid treatment, maintaining appropriate hygiene related to mobiles, self-monitoring measures, and official inspections were considered as *Salmonella* control measures applied by mobile feed mixers. In the case of pig farms, costs included in the assessment were *Salmonella* sampling, pest control, maintaining appropriate hygiene and cleanliness in feed storages and feeding facilities, and acid treatment when using liquid feeding (about 70% of farms).

The costs were assessed by first estimating the total annual cost of monitoring and preventive control measures. These costs were obtained from the stakeholder survey and interviews. Second, a share of these costs was attributed to pig feed in relation to the share of manufactured pig feed of all feed, since especially commercial feed production operators purchase materials and produce feed for many types of animals, and further to *Salmonella* control, as all the measures besides *Salmonella* sampling were assessed to be carried out also to prevent other diseases than *Salmonella*. The share attributed to *Salmonella* was evaluated by the feed sector experts individually to each measure, and they represent the proportion of costs that could be saved if *Salmonella* control were to be discontinued. This approach was chosen in order to take into account that preventive measures may mitigate both *Salmonella* and other diseases. As feed heat treatment would be carried out to some extent also when there was no mandatory *Salmonella* control, zero percent of the costs of treatment equipment maintenance and installation costs, and 20% (feed mills), 50% (mobile mixers), and 10% (farms) of the labor and material costs were assigned to *Salmonella*. Overall, 25% of the costs of official feed control, maintenance of appropriate hygiene and cleanliness, pest control (except 14% for feed mills), and self-monitoring (except 50% for feed mills) were assumed to be attributed to *Salmonella*. Potential impacts of preventive costs to market-clearing prices and quantity traded were not considered in the current analysis because the costs were fairly small when compared to the volume of Finnish pork production.

The parameters assumed to represent the costs of preventive measures in the current control scenario are provided in **Table 2**. **Table 1** summarizes the proportion of preventive and control costs incurred in the reduced *Salmonella* control scenario when compared to the current control policy scenario.

Cost of Human Salmonellosis and *Salmonella* Contaminations in the Pork Chain

As a consequence of the *Salmonella* control, fewer *Salmonella* contaminations along the pork supply chain and fewer human cases of salmonellosis can occur, thus reducing the costs of illness and contaminations along the food supply chain. The costs related to *Salmonella* were first estimated per *Salmonella* case, and then the number of cases was simulated for the two control scenarios by using a seeded Monte Carlo simulation model programed in MATLAB R2014b 8.4.0.150421 (MathWorks Inc., USA) to calculate the total annual costs of *Salmonella* contaminations and infections.

Costs caused by *Salmonella* contaminations included the statutory measures and additional voluntary measures taken by feed importers, feed mills, mobile feed mixers, pig farms, and slaughterhouses in accordance with the current control policy to eliminate *Salmonella* when it was simulated to occur in the pork supply chain. Measures included additional samples taken to verify *Salmonella* contamination and freedom from the bacterium; washing, cleaning, and disinfecting of facilities contaminated with *Salmonella*; and the treatment of contaminated feed. *Salmonella*-positive findings had to be communicated to authorities who are in charge of further actions carried out in cooperation with the feed business operator. If a sample from a feed consignment imported from the EU or from outside the EU was found positive for *Salmonella*, the contaminated feed was assumed to be treated with heat or acid. In the event of *Salmonella* contamination in pigs or pig farms, the cost included the treatment or culling and rendering of infected animals, business interruptions caused by restrictive measures which prevent the farm from selling animals, labor effort by authorities and stakeholders to handle the case of *Salmonella*

TABLE 2 | Parameter values assumed to represent the costs (€1,000 per year) of preventive measures in the current *Salmonella* control scenario per different stakeholder group.

Cost item	Feed importation	Feed mills	Mobile mixers	Pig farms	Source or method of data extraction
Sampling as self-monitoring	42	150	1.8	44	Survey, expert interview
Hygiene and cleaning		24	0.9	364–756	Survey
Pest control		1		28	Expert interview
Time used for other self-control measures		9	0.3–1.0	9–10	Survey
Feed treatments		974–1,499	1.0	67–329	Survey, Wierup and Widell (31)
Official control and sampling	56	17–18	2.8–3.4		Expert interview, national monitoring data
Prolonged storage	7–11				Expert interview
Total	105–109	1,174–1,701	5–6	512–1,166	

Empty items in the table were assumed zero.

contamination, and costs caused by infections in humans (lost working time, visits to the doctor, hospitalization, mortality, and secondary diseases).

The economic burden of *Salmonella* and its sequela in humans was estimated by using the disability adjusted life year (DALY) method. DALY is a non-monetary approach to estimate health implications of a disease. The average cost per human infection was estimated to range from €530 to €620 per case. This includes the cost of health care and productivity loss of acute symptoms (gastroenteritis with a raised body temperature and bloody diarrhea), sequela (reactive arthritis, inflammatory bowel disease, and irritable bowel syndrome), and death. Death was valued at €55,000 per lost human life year (32). It was evaluated that the true number of *Salmonella* infections would be 11.5-fold (21) compared to the annual number of reported cases and that although a productivity loss can occur due to absence from work, 80% of cases would not require any acute health care as they were asymptomatic. Symptoms requiring health care were divided further into different severities, ranging from the visit to a general practitioner to the hospitalization of the patient.

Table 3 illustrates the cost parameters used to simulate the costs of *Salmonella* contaminations. All parameters (mean, median, standard deviation (SD), percentiles) describing the prevalence of *Salmonella* at different stages of the supply chain were obtained from Rönnqvist et al. (37) [further described in Välttilä et al. (38)]. Parameters for the prevalence of *Salmonella* in pig feed, feed materials, and feed-related facilities are described in **Appendices 1** and **2** for the current control scenario.

Differences Between Current and Reduced Control Scenarios

Under the reduced control scenario, fewer measures were taken to prevent *Salmonella* from occurring in feed. In the event that *Salmonella* was simulated to occur in feed or feed handling facilities, no action to eradicate *Salmonella* was assumed to be taken. Hence, parameter values for the prevalence of *Salmonella* in feed materials and feeds were not of importance in the reduced control scenario when considering the cost implications of prevalence on eradication measures applicable to feed. By contrast, *Salmonella* contaminations observed in pigs or pig farms, pork, or slaughterhouses were expected to lead to the same measures being taken in both current and reduced control scenarios.

Parameters, which represent the prevalence of *Salmonella* in pigs (i.e., Papp), the probability for infection due to feed (Pft_k), and the annual prevalence of *Salmonella* infections in humans (P_m), were the most important parameters differing between the scenarios, because in the reduced control scenario, *Salmonella* contamination of feed was not considered to lead to an action. Under the current control policy scenario, the apparent prevalence of *Salmonella* in pigs was assumed to be presented by a parameter value of 0.139% (SD 0.061), when feed was given to sows, and by a parameter value of 0.074% (SD 0.030), when feed was given to fattening pigs. The number of human cases was simulated by using three distributions. It was assumed that of 337 reported cases in 2013, multiplied by an underreporting factor of 11.5, 12.29% (SD 3.756) were associated with pig meat, and of cases associated with fattening pigs, 33.63% (SD 14.62) were associated with pig feed. Under the reduced control scenario, the number of cases in humans and pigs was simulated to be 55.42 (SD 31.54) times the number of cases simulated under the current control policy scenario.

Sensitivity Analysis

Previous sections described the baseline parameter values used to simulate the costs of *Salmonella* control, *Salmonella* contaminations, and human cases associated with the current pig feed *Salmonella* control, as well as with a reduced control policy scenario. In addition to these, several sensitivity analysis scenarios were simulated. In the sensitivity analysis scenarios reported in the Results section, the costs parameters for the prevention and monitoring measures were doubled (i.e., increased twofold *ceteris paribus*), compared to the baseline scenario or the cost parameters for measures taken when *Salmonella* has been detected (contaminations or human cases), which were halved (i.e., decreased 0.5-fold *ceteris paribus*). The parameters were adjusted (either increased or decreased) separately for feed importation, feed manufacturing, pig farms and the slaughtering phase, and human cases (one stakeholder group at a time); for all prevention and monitoring measures simultaneously; and for all contaminations and human cases simultaneously.

TABLE 3 | Parameter values assumed to represent the costs [mean cost (SD in parentheses) or range of variation] of a *Salmonella* contamination, the costs of human cases, and the costs of measures required to eradicate *Salmonella* from feed materials, feed manufacturing, feed storage, or feed processing facility; from a pig farm; or from a slaughterhouse.

Variable	Parameter value	Source or method of data extraction
IMPORTATION		
Treatment, € per lot	46,849 (SD 2,237)	Expert interview
Extra samples, € per batch	3,938 (SD 2,809)	Expert interview, laboratory
Extra rent of warehouse, € per batch	719 (SD 343)	Expert interview
FEED MANUFACTURING		
Disinfection and cleaning of the mill environment, € per case	1,000–1,500	Survey
Disinfection and cleaning of feed manufacturing line, production interruption for a week, additional work and compensations paid to the customers, € per case	167,500–390,000	Survey
PIG FARMS		
Cleaning and disinfecting a piggery, € per sow	160–431	Expert interview
Cleaning and disinfecting a piggery, € per fattening pig	106–190	Expert interview
Culling and rendering, € per farm	1,640	Authors' calculations
Culling and rendering in addition to farm, € per sow	49.50	Lyytikäinen et al. (33)
Culling and rendering in addition to farm, € per fattening pig	16	Lyytikäinen et al. (33)
Value of rendered feed, € per sow	10.35	Heinola et al. (34)
Value of rendered feed, € per fattening pig	4.04	Heinola et al. (34)
Official inspections, sampling, and self-monitoring, € per sow	139	Authors' calculations based on the feed law
Official inspections, sampling, and self-monitoring, € per fattening pig	62	Authors' calculations based on the feed law
Restricted measures, duration in days	21–259	Evira
Lost value of culled animals and costs due to business interruptions, € per fattening pig	102 + 0.41*duration of restrictive measures	Niemi et al. (35)
Lost value of animals and costs due to business interruptions, € per fattening pig (pigs not culled)	12.7 + 0.47*duration of restrictive measures	Estimated with a model similar to Niemi et al. (36)
Lost value of animals and costs due to business interruptions, € per sow (pigs culled)	665 + 0.53*duration of restrictive measures	Estimated with a model similar to Niemi et al. (36)
Lost value of animals and costs due to business interruptions, € per sow (pigs not culled)	0.6 + 1.3*duration of restrictive measures + $4.8*10^{5*}$duration of restrictive measures	Estimated with a model similar to Niemi et al. (36)
SLAUGHTERHOUSE		
Extra samples, cleaning of slaughterhouse, € per case	1,070–14,620	Expert interview
HUMAN CONTAMINATION		
Health care, sequela (IBS, Rea, IBD), € per case on average	530–620	Authors' calculations
Feed-borne salmonellosis, annual loss of DALYs because of acute symptoms in Finland	0.04	Authors' calculations
Feed-borne salmonellosis, annual loss of DALYs because of fatality in Finland	0.97	Authors' calculations
Feed-borne salmonellosis, annual loss of DALYs because of sequela in Finland	1.43–3.64	Authors' calculations

RESULTS

Simulated Baseline Costs

In the current pig feed *Salmonella* control policy scenario, the total costs of measures to monitor and prevent *Salmonella* in pig feeds were €1.8–3.0 million per year (**Table 4**), depending on whether a high or a low estimate for the cost of control measures was used to appreciate the current control program. Costs related to the importation, commercial feed manufacturing, and farms were €0.1 million, €1.2–1.7 million, and €0.5–1.2 million per year, respectively. Under the current control scenario, simulated costs of *Salmonella* contamination at feed import process were on average €1.8 million. *Salmonella* contamination of feed origin at pig farms resulted annually, on average, in €0.4 million and at slaughterhouses in €0.1 million in losses. The costs of human salmonellosis of feed origin were simulated on average at €0.1 million per year for the current control policy. The average total cost of *Salmonella* contamination under the current control policy scenario was therefore €2.4 million, varying in 95% of simulations within the range of €0.3–6.1 million. Hence, the total costs of preventive and monitoring measures plus *Salmonella* contaminations were €4.2–5.4 million per year, with 95% of simulated years falling between €2.1 and €9.1 million.

In the reduced control scenario, the monitoring and prevention costs were decreased down to €1.1–2.1 million. Hence, the potential savings were only €0.7–0.9 million when compared to the current *Salmonella* control policy scenario. The

TABLE 4 | Simulated cost of *Salmonella* prevention and monitoring and *Salmonella* contaminated pig feed, pigs, and human infections (€ million per year, 95% range of variation within brackets).

	Current control scenario			Reduced control scenario		
	Low cost control	**High cost control**	**[CI 95%]**	**Low cost control**	**High cost control**	**[CI 95%]**
PREVENTION AND MONITORING						
Measures at import and storage	0.1	0.1		0	0	
Measures at feed manufacturing[a]	1.2	1.7		0.6	0.9	
Measures at pig farms	0.5	1.2		0.5	1.2	
Subtotal	1.8	3		1.1	2.1	
COSTS CAUSED BY CONTAMINATIONS						
Contamination at import or storage	1.8	1.8	[0.0, 4.5]	0.0	0.0	[0.0, 0.0]
Contamination at feed factory	0.0	0.0	[0.0, 0.1]	0.0	0.0	[0.0, 0.0]
Contamination at farm[b]	0.4	0.4	[0.1, 1.1]	20.5	20.5	[0.6, 80.7]
Costs to slaughterhouse	0.1	0.1	[0.0, 0.4]	6.0	6.0	[0.2, 26.1]
Costs of human infections[c]	0.1	0.1	[0.0, 0.3]	6.2	6.2	[0.1, 22.0]
Subtotal[c]	2.4	2.4	[0.3, 6.1]	32.7	32.7	[1.1, 123.9]
Total costs	4.2	5.4		33.8	34.8	

[a] Includes the costs of mobile mixers. [b] Salmonella detected in the pigs or their environment. [c] The costs of human cases were simulated assuming a fixed average cost per case.

lower level of control resulted in fewer preventive measures being applied, which decreased the costs, but likely increased the possibility of *Salmonella* to occur, as seen in the prevalence parameters originating from the risk assessment study (28). This increased the total costs of *Salmonella* contaminations, which were on average €32.7 million. This estimate included the costs of human cases. The contamination costs estimated for pig farms were on average €20.5 million, but the costs incurred at slaughterhouses were partially related to measures taken because of contaminations at farms. The increase in the costs of human salmonellosis was on average €6.2 million, which was more than the costs saved because of reduced preventive and monitoring measures. The total costs of reduced control scenario were estimated on average to be €33.8–€34.8 million per year.

The current control policy provided on average €29.4 million in annual benefits when compared to the reduced control scenario. The additional prevention and monitoring costs of the current control policy were estimated to be within the range of €0.7 to €0.9 million per year, whereas saved costs of contaminations under the current control policy were on average €30.3 million when compared to the reduced control scenario (in 95% simulations between €0.8 and €117.8 million).

The results showed a substantially larger variation in the costs of the reduced control scenario than the current control scenario (**Figure 1**; **Table 4**). The average estimates were elevated in individual years when larger outbreaks were experienced. Hence, the simulated costs of *Salmonella* control were substantially lower in the current control policy scenario than in the reduced control scenario. In the current analysis, the costs of human cases were simulated assuming a fixed average cost per case. Separating the costs by different types of human infections would have further increased the variation of simulated costs as fatality cases carried a high cost.

Sensitivity Analysis

Figure 2 reports the results for sensitivity analyses where the cost parameters of measures to prevent and monitor *Salmonella* were doubled, or the cost parameters of measures taken when *Salmonella* has been detected were halved. As **Figure 2** illustrates, the costs of the current control policy were on average <€8.5 million in all sensitivity analysis scenarios representing the current control policy, whereas the costs simulated for the reduced control were on average between €21.5 and €37 million in all sensitivity scenarios. Therefore, the current control policy was financially preferred over the reduced control policy in the scenarios which were analyzed.

The results were the most sensitive to costs associated with a contamination in pigs (at farms or at slaughterhouses) and feed on pig farm. This can be anticipated because in the reduced control scenario, these costs represented approximately three-fourths of the total costs. Changes in the modeling assumptions regarding human cases of *Salmonella* also had a potentially substantial impact of the total costs. Adjusting assumptions regarding the cost parameters of prevention and control measures before *Salmonella* had occurred had a fairly small impact on the total costs.

Further analyses indicated that the costs associated with measures taken upon *Salmonella* contamination or associated with human cases had to decrease by at least 90% (*ceteris paribus*) before the costs of reduced control policy would have been, on average, at the same level, as costs simulated for the current control policy scenario. However, even then, the reduced control policy was simulated to show a larger variation of costs when compared to the current control policy. This was because the costs of contaminations and

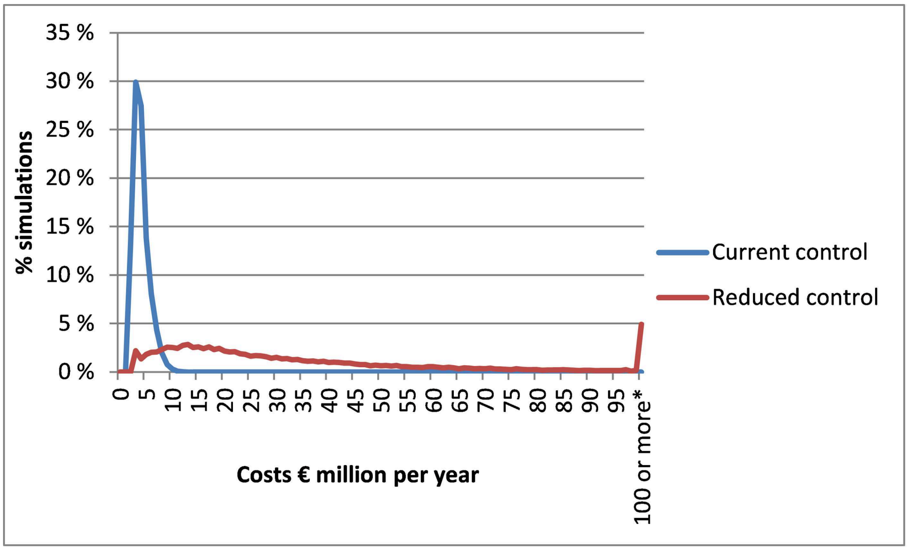

FIGURE 1 | Distribution of costs simulated for measures of prevention, monitoring, and eradication of *Salmonella* in the pig feed chain, and human cases originating from *Salmonella* in the pig feed chain. *Simulations exceeding €100 million per year are aggregated in this category.

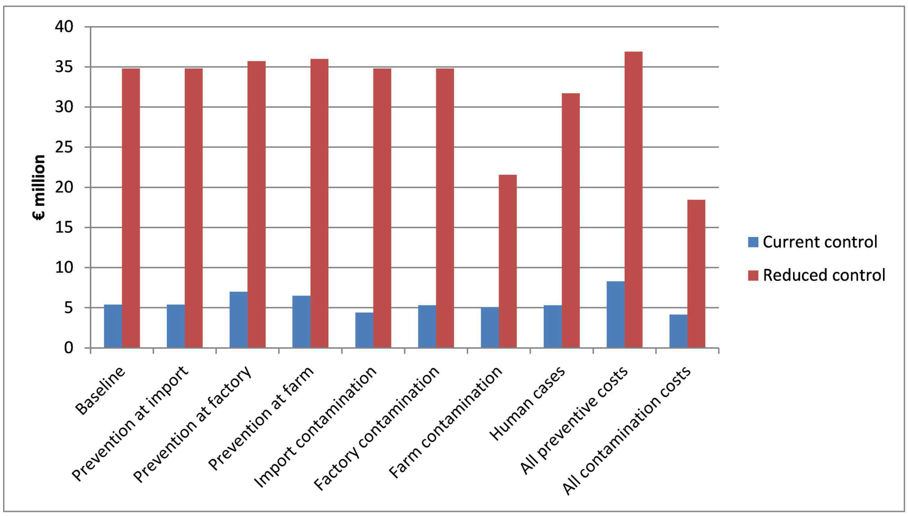

FIGURE 2 | The average total costs of pig feed *Salmonella* control simulated for the baseline parameter values of "current control" and "reduced control" policy scenarios, as well as for both policies, so that the costs parameters for prevention and monitoring measures were doubled ("Prevention…") when compared to the baseline scenario or the cost parameters for contaminations or human cases, which were halved ("Contamination…," "Human cases") either for one stakeholder group at a time or for all groups simultaneously.

human cases varied more than the costs of prevention and monitoring measures.

DISCUSSION

Economic Rationale of *Salmonella* Control in Pig Feed

In this study, the costs and benefits of current *Salmonella* control policy concerning pig feeds were assessed and compared to a reduced control scenario. The results suggested that the current pig feed *Salmonella* control policy is financially profitable as it reduced costs caused by *Salmonella* contaminations in pigs, in their environment, or in pork and human infections. Currently *Salmonella* is controlled already early in the pork supply chain. While rather small amount of costs could be saved by relaxing the current prevention and monitoring measures, simultaneously much larger additional costs would be incurred through increased human infection costs and costs caused by eradicating *Salmonella* from pigs, pig farms, and slaughterhouses. Therefore, pig feed *Salmonella* control provides both public health benefits to society and supports FSCP in it goals. The results extend earlier research results on that that FSCP is economically viable in the poultry sector [e.g., Kangas et al. (19)] and that FSCP achieves high food safety targets of meat, milk, and egg food chains without high costs (16).

Our results are in line with those of the FCC consortium (21) report in the sense that a control option with an increased sampling as well as feed control measures either with transport and slaughterhouse measures was financially profitable in both studies for Finland, and in the case of the FCC consortium (21) also for some other countries. However, our study did not look specifically for other measures than those related to feed control. In Sweden, Sundström et al. (23) found that it was not cost-effective to introduce reduced *Salmonella* control strategies. Lawson et al. (22) indicated in their comparison that using home-mixed or acidified feeds for Danish pigs was financially beneficial in some cases. Gavin et al. (24) found for the United Kingdom that two interventions using wet feed and organic acids in feed were able to provide a financial net benefit to the farms as means to control for *Salmonella*. By contrast, Goldbach and Alban (26) found that using specific home-mixed feed in herds with slaughter pigs and using acidified feed for slaughter pigs as means to control for *Salmonella* in Denmark were not socioeconomically profitable. Comparing these results and studies therefore suggests that an intervention to control *Salmonella* is not financially profitable *per se* because the profitability is influenced by context-specific factors.

The benefits of controlling *Salmonella* in pig feeds likely depends on how much feeds contribute to the risk of *Salmonella* and what is the prevalence of *Salmonella* in the country. As long as the prevalence of *Salmonella* is at the current low level, it makes sense to try to maintain the current situation in Finland and eliminate emerging cases as this can be done with a reasonably low level of costs. The results of Jensen and Unnevehr (27) suggest that intervention costs increase when the desired level of pathogen approaches zero. Miller et al. (25) suggested that changes in *Salmonella* status during processing are more important for human health risk and have a higher benefit–cost ratio when compared with on-farm strategies for *Salmonella* control. They noticed that in the contexts of the United States, benefit–cost ratios were less than unity for the on-farm strategy of meal feeding. This does not comply with our results.

Reducing feed-related *Salmonella* control measures from the current level, the risk of *Salmonella* prevalence could rise and this would have negative economic consequences to society. In the alternative situation, the number of feed-borne human salmonellosis cases would increase, which would have a negative effect on the health care cost, but also the productivity of labor due to more absences from work. Approximately €6.2 million were saved because of improved public health (i.e., human cases) under the current *Salmonella* control policy. Therefore, the pig feed *Salmonella* control was justified already because of public health issues. Most of the saved costs were associated with lower costs incurred due to contaminations in pigs (whether observed at farm or at slaughterhouse) or in their environment. These costs were saved because of reduced prevalence of *Salmonella* in pigs or in their environment and measures associated with these contaminations because of FSCP. Hence, effective pig feed *Salmonella* control can support effectiveness of FSCP, which further supports public health in Finland. Pig feed *Salmonella* control policy and FSCP should therefore be examined jointly. An important aspect which can be generalized beyond the context of this study is that risk management measures can be complementary when applied in a livestock supply chain and the use of joint inputs is involved, and therefore, possible joint effects of risk management measures affecting the same outcome indicators should be considered.

Potential limitations of our study are related to the scenarios which were investigated. Besides the two scenarios, we did not look at other intervention scenarios. Hence, there may be other scenarios with slightly reduced or increased control options which could be preferred over the current control policy. This includes novel combinations where both pig feed *Salmonella* control policy and FSCP are adjusted from their current status. The scenarios were also developed by using information from a limited number of feed operators, which, together with missing responses, causes uncertainty about the parameter values used. Specific conditions prevailing in Finland may limit the applicability of the results to other contexts. Another potential limitation is related to the appraisal of joint costs. This refers to the costs of measures such as biosecurity, which are applied to mitigate several diseases. Accounting for a higher proportion of these costs to be related to *Salmonella* prevention would increase the costs of the current control scenario. However, apart from feed heat treatment, the costs were rather modest.

Stakeholder Incentives

Strict liability currently defines responsibilities regarding feed-related *Salmonella* contaminations. These liabilities are mainly faced by the commercial feed manufacturers as they must indemnify damage caused by contaminated feed for buyer if their feed does not meet the requirement of the law, even though the contamination is not caused by intent or negligence. This can be a financially heavy responsibility. The reduced control scenario examined a situation where more responsibility on the contamination costs and human cases was transferred to the pig industry and consumer. Since the beneficiaries of strict liability are mainly farms which purchase pig feed, the meat industry, and consumers who face reduced risk of salmonellosis both directly and indirectly through support that it provides to FSCP's goals, an important policy question is whether the feed suppliers are able to recover their costs through feed prices.

The incentive aspect can be extended beyond the context of this study. In order to provide sufficient incentives to comply with a given level of liability, it would be important that feed suppliers can recover their costs, for instance, through an insurance policy, a co-finance mechanism involving the supply chain parties, or from the markets. Even if the official pig feed *Salmonella* control policy would be relaxed, many similar actions, and thus their costs, would be taken as they are part of the policy to control animal diseases and to maintain appropriate feed hygiene. Official control and self-control measures should therefore be considered jointly.

The cost aspect is relevant because previous studies show in the context of farms that there is a clear inverse relationship between the willingness of farmers to adopt a biosecurity measure to reduce *Salmonella* and its estimated cost [Niemi et al. (39), Fraser et al. (40)]. For an individual farm in Finland, the damage caused by *Salmonella* contamination can be substantial. An elevated risk of *Salmonella* can occur when interventions are applied only at later stages of the supply chain. With the statutory requirement to eliminate *Salmonella*, the consequences would be costly for the pig producers. Insurance policies to cover the risk of *Salmonella* contamination exist, but they are sometimes considered expensive. This is a challenge not only in Finland but also in various other countries where livestock disease insurance is available in the market [cf. Heikkilä and Niemi (41)].

CONCLUSION

The current pig feed *Salmonella* control policy of Finland is economically profitable because it reduces the costs caused by *Salmonella* contaminations along the food chain with low costs. This provides public health benefits which are higher than the costs of pig feed *Salmonella* control. Pig feed *Salmonella* control can support the effectiveness of a broader control program (FSCP), which further enhances public health. Pig feed *Salmonella* control policy and FSCP should therefore be examined jointly. In order to increase the acceptability of current policy, greater attention to the allocation of financial responsibilities (costs and benefits) regarding the control measures may be required.

DATA AVAILABILITY

The datasets for this manuscript are not publicly available because the data contain confidential information which cannot be revealed to parties other than scientists who were involved in the study. Requests to access the datasets should be directed to jarkko.niemi@luke.fi.

AUTHOR CONTRIBUTIONS

KH carried out a financial analysis on the current control program. KH and MS carried out most of the data collection. PT led the risk assessment work. JN led the economic analysis and conducted stochastic simulations to assess the overall costs and costs caused by *Salmonella* contaminations. JN and KH drafted the manuscript. All authors contributed to the planning of the study and reporting the results.

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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.2019.00200/full#supplementary-material

REFERENCES

1. WHO. *WHO Estimates of the Global Burden of Food-Borne Diseases. Food-Borne Disease Burden*. Geneva: World Health Organization (2015). p. 268.
2. Ao TT, Feasey NA, Gordon MA, Keddy KH, Angulo FJ, Crump JA. Global burden of invasive nontyphoidal Salmonella disease, 2010. *Emerg Infect Dis*. (2015) 21:941–949. doi: 10.3201/eid2106.140999
3. European commission. *RASFF—The Rapid Alert System for Food and Feed—2017 Annual Report*. Luxembourg: Publications Office of the European Union: Brussels (2018). Available online at: https://ec.europa.eu/food/sites/food/files/safety/docs/rasff_annual_report_2017.pdf
4. EFSA, ECDC. The European Union summary report on trends and sources of zoonoses, zoonotic agents and food-borne outbreaks in 2017. *EFSA J*. (2018) 16:5500:262. doi: 10.2903/j.efsa.2018.5500
5. THL (2019). *Infectious Disease Register (in Finnish)*. Available online at: https://sampo.thl.fi/pivot/prod/fi/ttr/shp/fact_shp (accessed February 28, 2019).
6. Wheeler JG, Sethi D, Cowden JM, Wall PG, Rodrigues LC, Tompkins DS, et al. Study of infectious intestinal disease in England: rates in the community, presenting to general. *BMJ*. (1999) 318:1046–50. doi: 10.1136/bmj.318.7190.1046
7. STM. *Elintarvike-erityistilanne -työryhmän muistio (in Finnish). Työryhmäraportti*. Helsinki: Sosiaali- ja terveysministeriö (1997). p. 7.
8. Osterberg J, Vågsholm I, Boqvist S, Lewerin SS. Feed-borne outbreak of Salmonella cubana in Swedish pig farms: risk factors and factors affecting the restriction period in infected farms. *Acta Vet Scand*. (2006) 47:13–21. doi: 10.1186/1751-0147-47-13
9. EFSA. Report of the Task Force on Zoonoses Data Collection on the analysis of the baseline survey on the prevalence of Salmonella in slaughter pigs, in the EU, 2006–2007, part A: salmonella prevalence estimates. *EFSA J*. (2008) 135:1–111. doi: 10.2903/j.efsa.2008.135r
10. EFSA. Scientific opinion on a quantitative microbiological risk assessment of Salmonella in slaughter and breeder pigs. *EFSA J*. (2010) 8:1547. doi: 10.2903/j.efsa.2010.1547
11. Andres VM, Davies RH. Biosecurity measures to control Salmonella and other infectious agents in pig farms: a review. *Compr Rev Food Sci F*. (2015) 14:317–335. doi: 10.1111/1541-4337.12137
12. Clark B, Panzone LA, Stewart GB, Kyriazakis I, Niemi JK, Latvala T, et al. Consumer attitudes towards production diseases in intensive production systems. *PLoS ONE*. (2019) 14:e0210432. doi: 10.1371/journal.pone.0210432
13. European Commission. *European Commission Decision 94/968/EC approving the Operational Programme for the Control of Salmonella in Certain Live Animals and Animal Products Presented by Finland*. Bussels: European Commission (1994).
14. MMMEEO. The Finnish Salmonella Control Programmes for live animals, eggs and meat. In: *Veterinary and Food Department*. Helsinki: Ministry of Agriculture and Forestry (1994). p. 41–41.
15. Mead G, Lammerding AM, Cox N, Doyle MP, Humbert F, Kulikovskiy A, et al. Salmonella on raw poultry writing committee. Scientific and technical factors affecting the setting of Salmonella criteria for raw poultry: a global perspective. *J Food Prot*. (2010) 73:1566–90. doi: 10.4315/0362-028X-73.8.1566
16. Maijala R, Ranta J, Seuna E, Peltola J. The efficiency of the finnish salmonella control programme. *Food Control*. (2005) 16:669–675. doi: 10.1016/j.foodcont.2004.06.003

17. Maijala R. The costs, benefits and effects of the *Salmonella* Control Programme—efficiency and viability in food safety promotion. In: *Proceeding of the Workshop on Analytical Methods in the Epidemiology of Zoonoses* (1998).
18. Maijala R, Peltola J. *Economics of Food Safety in Finland – Case: National Salmonella Control Program*. Helsinki: Agricultural Economics Research Institute (2000).
19. Kangas S, Lyytikäinen T, Peltola J, Ranta J, Maijala R. Costs of two alternative Salmonella control policies in Finnish broiler production. *Acta Vet Scand*. (2007) 49:35. doi: 10.1186/1751-0147-49-35
20. Maijala R, Nuotio L, Junttila J. The costs–benefits analysis of the Salmonella Control Programme in Finland (in Finnish). *Suomen Siipikarja*. (1998) 2:30–1.
21. FCC Consortium. *Analysis of the Costs and Benefits of Setting a Target for the Reduction of Salmonella in Breeding pigs for European Commission Health and Consumers Directorate-General* SANCO/2008/E2/056. (2011). Available online at: https://ec.europa.eu/food/sites/food/files/safety/docs/biosafety_food-borne-disease_salmonella_breeding-pigs_salm-cost-benefit.pdf (accessed February 28, 2019).
22. Lawson LG, Jensen JD, Christiansen P, Lund M. Cost-effectiveness of Salmonella reduction in Danish abattoirs. *Int J Food Microbiol*. (2009) 134:126–32. doi: 10.1016/j.ijfoodmicro.2009.03.024
23. Sundström K, Wahlström H, Ivarsson S, Sternberg Lewerin S. Economic effects of introducing alternative Salmonella control strategies in Sweden. *PLoS ONE*. (2014) 9:e96446. doi: 10.1371/journal.pone.0096446
24. Gavin C, Simons RRL, Berriman ADC, Moorhouse D, Snaly EL, Smith RP, et al. A cost–benefit assessment of Salmonella—control strategies in pigs reared in the United Kingdom. *Prev Vet Med*. (2018) 160:54–62. doi: 10.1016/j.prevetmed.2018.09.022
25. Miller GY, Liu X, McNamara PE, Barber DA. Influence of *Salmonella* in pigs preharvest and during pork processing on human health costs and risks from pork. *J Food Prot*. (2005) 68:1788–98. doi: 10.4315/0362-028X-68.9.1788
26. Goldbach SG, Alban L. A cost–benefit analysis of Salmonella—control strategies in Danish pork production. *Prev Vet Med*. (2006) 77:1–14. doi: 10.1016/j.prevetmed.2005.10.008
27. Jensen HH, Unnevehr LJ. HACCP in pork processing: costs and benefits. In: Unnevehr LJ, ed. *The Economics of HACCP—Costs and Benefits*, St. Paul: Eagan Press (2000). p. 29–44.
28. Rönnqvist M, Välttilä V, Heinola K, Ranta J, Niemi J, Tuominen P. Risk assessment and cost–benefit analysis of Salmonella in feed and animal production. *Evira Research Reports 3/2018*. Helsinki: Finnish Food Safety Authority (2018).
29. Luke. *Natural Resources Institute Finland. 2015, 2014—Last Update, Meat Production, Year 2013 and 1/2014*. Helsinki: Natural Resources Institute Finland (2015).
30. Evira (2015). *Feed Statistics*. Helsinki: Feed control, Finnish Food Safety Authority.
31. Wierup M, Widell S. Estimation of costs for control of Salmonella in high-risk feed materials and compound feed. *Infect Ecol Epidemiol*. (2014) 4:23496. doi: 10.3402/iee.v4.23496
32. Asikainen A, Pärjälä E, Kettunen T, Savastola M, Niittynen M, Tuomisto J. *URGENCHE: kasvihuonekaasupäästöjen vähennystoimenpiteiden vaikutukset päästöihin sekä väestön terveyteen ja hyvinvointiin Kuopiossa*. Kuopio (2014). Available online at: https://www.kuopio.fi/c/document_library/get_file?uuid=29aa344b-058c-42f6-9646-61301b0dde82&groupId=12141 (accessed February 28, 2019).
33. Lyytikäinen T, Niemi J, Sahlström L, Virtanen T, Lehtonen H. *The Spread of Foot-and-Mouth Disease (FMD) Within Finland and Emergency Vaccination in case of an Epidemic Outbreak*. Evira Research Reports 1/2011. Helsinki: Finnish Food Safety Authority Evira (2011). p. 147. Available online at: http://www.evira.fi/portal/en/evira/publications/?a=view&productId=240
34. Heinola K, Niemi JK, Myyrä S. *Index Insurance as an Income Stabilisation Tool in the Finnish Pig Sector (in Finnish)*. MTT Raportti 71. Helsinki: MTT (2012).
35. Niemi JK, Pietola K, Sévon-Aimonen M. Hog producer income losses under contagious animal disease restriction. *Acta Agric Scand C Food Econ*. (2004) 1:185–94. doi: 10.1080/16507540410019728
36. Niemi JK, Sevón-Aimonen M-L, Partanen K, Pietola K. Modeling the costs of postpartum dysgalactia syndrome and locomotory disorders on sow productivity and replacement. *Front Vet Sci*. (2017) 4:1–12. doi: 10.3389/fvets.2017.00181
37. Rönnqvist M, Välttilä V, Ranta J, Tuominen P. Salmonella risk to consumers *via* pork is related to the Salmonella prevalence in pig feed. *Food Microbiol*. (2018) 71:93–97. doi: 10.1016/j.fm.2017.03.017
38. Välttilä V, Ranta J, Rönnqvist M, Tuominen P. Bayesian model for tracing Salmonella contamination in the pig feed chain. *Food Microbiol*. (2018) 71:82–92. doi: 10.1016/j.fm.2017.04.017
39. Niemi JK, Sahlström L, Virtanen T, Kyyrö J, Lyytikäinen T, Sinisalo A. Farm characteristics and perceptions regarding costs contribute to the adoption of biosecurity in Finnish pig and cattle farms. *Rev Agric Food Environ Stud*. (2016) 97:215–23. doi: 10.1007/s41130-016-0022-5
40. Fraser RW, Williams NT, Powell LF, Cook AJC. Reducing Campylobacter and Salmonella infection: two studies of the economic cost and attitude to adoption of on-farm biosecurity measures. *Zoonoses Public Health*. (2010) 57:e109–15. doi: 10.1111/j.1863-2378.2009.01295.x
41. Heikkilä J, Niemi. JK. *Alternatives for Financing Animal Disease Epidemics: Principles, Practices and Propositions (in Finnish)*. MTT:n selvityksiä 168. Helsinki: MTT (2008). p. 126. Available online at: http://urn.fi/URN:ISBN:978-952-487-211-9

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An Epidemiological and Economic Simulation Model to Evaluate Strategies for the Control of Bovine Virus Diarrhea in Germany

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Models can be used to plan, evaluate, and improve programs for animal disease control. In Germany, a nationwide compulsory program to eradicate Bovine viral diarrhea (BVD) is in force since January 2011. As it is associated with substantial expenditures, the program is currently under revision. To provide the basis for a science-based decision on the future course of BVD control in Germany, we evaluated 13 scenarios (sc1-13) with respect to the chance of reaching freedom from disease and their economic implications for a period of 20 years (2011–2030). To simulate the impact of different control strategies on disease dynamics, a disease spread model was developed. To estimate the effects of a transient infection (TI) on animal level, a gross margin analysis was performed. To assess the value of cattle that died prematurely, a valuation model was used. Finally, an economic model was developed to perform a cost-benefit analysis and to compare each control scenario with a baseline setting with no BVD control. Costs comprised the expenditures for diagnostics, vaccination, preventive culling, and trade restrictions. Benefits were animal and production losses avoided by having control measures in place. The results show that reducing the PI prevalence on animal level to 0% is only feasible in scenarios that combine antigen or antibody testing with compulsory vaccination. All other scenarios, i.e., those based exclusively on a “test and cull” approach, including the current control program, will, according to the model, not achieve freedom of BVD by 2030. On the other hand, none of the scenarios that may lead to complete BVD eradication is economically attractive [benefit-cost ratio (BCR) between 0.64 and 0.94]. The average direct costs of BVD in Germany are estimated at 113 million Euros per year (34–402 million Euros), corresponding to 28.3 million Euros per million animals. Only the concepts of the former and the current national BVD control program (“ear tag testing and culling”) may reduce the BVD prevalence to 0.01% with an acceptable BCR (net present value of 222 and 238 million Euros, respectively, with a BCR of 1.22 and 1.24).

Keywords: bovine viral diarrhea, disease control, economic analysis, cost-benefit analysis, agent-based model, dairy cattle

INTRODUCTION

Bovine viral diarrhea (BVD) is an important infectious disease in cattle with a major economic impact that varies within and between countries (1, 2). Most of the economic damage is caused by a lower reproductive performance in dairy cattle, including reduced conception rate, abortion and reduced milk yield. Depending on the stage of pregnancy at the time of infection, vertical BVD transmission may result in abortion/stillbirth, congenital defects, growth retardation or the birth of persistently infected (PI) calves, which are often small and unthrifty, have increased susceptibility to other diseases and may eventually die from mucosal disease (3). Horizontal transmission can occur by direct or indirect contact with virus-shedding animals. The causative agent, BVD virus (BVDV), belongs to the genus Pestivirus of the family *Flaviviridae* and is divided into two genotypes: Pestivirus A (previously BVDV-1) and Pestivirus B (previously BVDV-2) (4). Although the existence of Pestivirus B has been confirmed in Germany (5), the predominant genotype in the country is Pestivirus A.

A number of countries in the European Union, e.g., Spain, do not monitor BVD at the national level (6). However, most countries have implemented voluntary or mandatory BVD control programs, which can lead to a significant decline in the PI prevalence (7). The programs differ in the way PI animals are detected, and in allowing or excluding vaccination. Some successful programs combine the test and cull strategy with vaccination, e.g., in Belgium, Ireland and Scotland (8). Others were successful without using vaccination, e.g., those implemented in Scandinavian countries, Austria and Switzerland (9–14). The economic impact of BVD and different control strategies has recently been reviewed in a number of publications (14–16).

According to the German statistical office (Destatis) and the Federal Office for Agriculture and Food, in 2017 there were 12.37 million heads of cattle in the country, including 4.2 million dairy cows, distributed in 143 thousand cattle farms. In Germany, the first voluntary BVD control program was developed in the late 1980s by the federal state of Lower Saxony (17). Central elements were the identification and elimination of PI animals and the systematic vaccination of all female offspring (18). Later, other federal states launched their own BVD control programs, on either a voluntary (e.g., Bavaria, North Rhine Westphalia, Lower Saxony) or a compulsory basis (e.g., Saxony-Anhalt) (19). However, the programs differed between the federal states and participation was at least in the beginning voluntary, with the consequence that little progress was achieved (20). There were also drawbacks in PI-free herds that had become seronegative and thus fully susceptible in an environment where infectious pressure of BVDV was high (21).

On 3 November 2004, BVD became a notifiable animal disease in Germany and on January 1, 2011, a nationwide compulsory BVD control program was started (22). At that time, the PI prevalence in Germany was at about 0.5% on animal level (23) and a limited proportion of the population was vaccinated against BVD. Consequently, all animals had to be tested for BVDV or its genome. The new regulations of 2011 introduced the testing of all newborn calves combining the cattle ear tag application with the sampling of a small ear tissue plug, which was subjected to BVDV testing (24). PI animals have to be eliminated (either immediately culled or slaughtered within seven days). It is also mandatory to test animals prior to movement if they have not been assigned a BVD status. Only cattle that have tested negative for BVDV ("unsuspicious animals") may be traded. If an animal tests positive for BVDV, it is either removed (usually slaughtered) or retested after 6 weeks to rule out a transient infection. The German BVD control program has always allowed the use of vaccines, since they are considered a useful addition for preventing the formation of PI calves. In Germany, one modified live and several inactivated BVD vaccines are currently registered and can be used in different vaccination schemes. Since 2009, all BVD vaccinations and test results are recorded at the individual animal level in the national animal identification database ("*Herkunftssicherungs- und Informationssystem für Tiere,*" HIT), which is used for the registration of cattle holdings, all cattle individually, and for movements of cattle. Reliable BVD data are available since mid-2011. Based on the time point and the results of the BVD tests, an algorithm integrated into HIT calculates the individual BVD status: (i) without status; (ii) unsuspicious, i.e., antibody negative or mother of negative calf; (iii) first test positive; (iv) PI animal, i.e., two consecutive positive tests, or positive test without confirmation, or a calf of a PI mother.

Between the onset of mandatory testing in January 2011 and December 2016, more than 34 million animals were tested, registered in the HIT database and assigned a BVD status. The proportion of PI affected farms (animals) was reduced from 3.44% (0.48%) in 2011 to 0.16% (0.02%) in 2016. Although no recent studies are available, the seroprevalence in Germany is still assumed at 10-25%, depending on the region (25). The national BVD control strategy is currently under revision. The following alternatives to the current control policy are under discussion: (1) Stop BVD control and monitoring[1] including a strict non-vaccination policy. (2) Continue controlling and monitoring BVD as laid down in the national regulation implemented from 2011 to 2016. (3) Proceed as in (2) with additional trade restrictions for BVD-affected cattle farms. (4) Continue BVD control as laid down in the current BVD regulation (antigen-detection by ear tag). (5) Proceed as in (4) with additional antibody testing (AbT) in individual or pooled serum/plasma samples from young stock between 9 and 12 months (so called "*Jungtierfenster*") (26, 27) and voluntary vaccination. (6) Proceed as in (5) with additional compulsory vaccination. In this study, we evaluated 13 scenarios including the current BVD control policy, different combinations of the above-mentioned alternatives, and a baseline scenario (no BVD control) with respect to the chance of disease eradication and the economic implications in a period of 20 years (2011–2030).

[1]**Control** means, a pre-defined control measure is carried out (e.g., culling, trade restriction, quarantine), if a BVDV positive animal is detected. **Monitoring** is a systematic measurement of animal health, where a positive result does not necessarily lead to action.

MATERIALS AND METHODS

Scenarios

Starting with the baseline scenario without any BVD control (sc1), we developed 12 alternative scenarios and simulated the course of BVD from 2011 onwards. In sc2, we simulated the former BVD control program that was in place in Germany 2011–2016. In sc3, we simulated the control program that is currently in place. In sc4, we simulated the immediate cessation of BVD control on July 1, 2017. The other nine scenarios were deduced from the current epidemiological situation and represent potential options for future BVD control based on various combinations of measures.

Each scenario is a chronological order of strategies; each strategy consists of a combination of measures (e.g., ear tag and vaccination; **Table 1**). All 13 scenarios start with the strategy "no BVD control" (sc1). By contrast, scenarios sc2-13 include the former BVD regulation as implemented on January 1, 2011. While sc2 represents only the continuation of the former BVD regulation (in place from 2011 to 2016), scenarios sc3-13 go beyond sc2 by including also the measures foreseen in the current BVD regulation as implemented on June 27, 2016. While sc3 represents the continuation of the current BVD regulation, sc4-13 implement different further strategies in the model from July 1, 2017 onwards.

Scenario 1 (sc1) reflects the basic situation, in which no control program is in place, i.e., no efforts are made to detect or remove PI animals. Thus, no vaccination expenses or other preventive expenditures are included in the economic model. This scenario is hypothetical, since Germany has implemented BVD control measures for a long time. Scenario sc1 was included to compare different intervention scenarios with a "baseline" scenario that does not include any intervention.

Scenario 2 (sc2) was designed according to the control program that was in place in Germany between 2011 and 2016 (former BVD regulation). This program included obligatory antigen screening (ear tag) in newborn calves (<7 days) and the removal of PI animals within 60 days after confirmation of a BVD positive test result. The strategy also included voluntary vaccination and individual antigen testing in adult animals before trading them.

Scenario 3 (sc3) combines the strategy of the former BVD regulation with the control program, which is in place in Germany since June 27, 2016 (new BVD regulation). Similar to sc2, it includes antigen screening (ear tag) in newborn calves (<7 days) as well as individual antigen testing in adult animals before trading and voluntary vaccination. In contrast to sc2, sc3 includes the removal of PI animals within 40 days (instead of 60 days in sc2) and a trade restriction of 40 days for farms after confirmation of a BVD infection in the herd.

Scenario 4 (sc4) is similar to sc3 but assumes that BVD control has stopped on July 1, 2017.

Scenario 5 (sc5) is similar to sc3 with the only difference that it includes compulsory vaccination starting on July 1, 2017.

Scenarios 6 and 7 (sc6, sc7) include antigen detection after birth or before trade (similar to sc2, sc3, and sc5). In addition, they also include AbT, either twice a year (sc6) or once a year (sc7) and PI removal within 40 days as well as trade restrictions of 40 days, but no vaccination.

Scenarios 8 and 9 (sc8, sc9) are similar to sc6 and sc7 and include AbT, either twice a year (sc8) or once a year (sc9), but in contrast to sc6 and sc7, they include compulsory vaccination.

Scenario 10 (sc10) only includes AbT twice a year.

Scenarios 11 and 12 (sc11, sc12) represent the decision to stop testing on July 1, 2017 and to switch to vaccination only, either immediately (sc11) or after a transitional period (sc12).

Scenario 13 (sc13) combines the measures of AbT twice a year and compulsory vaccination. Testing of ear tags plugs is stopped after a transition period of 1 year (06/2018) to allow the whole cattle population to become protected by vaccination against BVD.

TABLE 1 | Overview of the 13 modeled BVD control scenarios.

Scenario	Strategies (start)				Measures	
	24/11/1983	01/01/2011	29/06/2016	01/07/2017		
1	1				No control	
2	1	2			Former regulation (ear tag)	
3	1	2	3		New regulation (ear tag, trade restrictions)	
4	1	2	3	1	No control	
5	1	2	3	4	Ear tag, compulsory vaccination	
6	1	2	3	5	Ear tag	AbT 2×/year
7	1	2	3			AbT 1×/year
8	1	2	3	6	Ear tag, compulsory vaccination	AbT 2×/year
9	1	2	3			AbT 1×/year
10	1	2	3	7		AbT 2×/year
11	1	2	3	8	Compulsory vaccination, stop testing	Inmediate stop
12	1	2	3			Slow stop
13	1	2	3	9	Compulsory vaccination	AbT 2×/year

The different colors represent different strategies. Each scenario is a chronological order of strategies; each strategy consists of a combination of measures.

Models

The evaluation of the eradication success and profitability of different BVD control scenarios was done in four steps. (1) An agent-based disease spread model (DSM) was developed to simulate the dynamics of BVD spread and immunity within the population. (2) A gross margin analysis (GMA) was performed to estimate the economic impact of a transient BVD infection. (3) To estimate the value of PI animals that prematurely die of BVD, we developed a stochastic animal valuation model (AVM). (4) We developed an economic model and performed a cost-benefit analysis (CBA) using the results of the DSM, GMA and AVM.

Disease Spread Model (DSM)

To simulate the dynamics of BVD in different scenarios, a stochastic, event-driven, hierarchical agent-based disease spread model (DSM) was developed. Within the DSM, trade was realized using a farm manager and a market. The farm manager keeps the size of the farms constant. When a farm has too many animals, it will sell animals to a market, if it needs animals it will buy animals from the market. These movements are based on trade criteria. If there is no demand on animals with a certain criteria, they will be slaughtered. Whenever there are not enough animals in the market, new animals are created (simulation of imports from EU member states). The DSM takes into account (i) five individual disease status, namely susceptible, transiently infected (TI), persistently infected (PI), recovered from transient infection, and vaccinated; (ii) disease transmission between animals, (iii) disease transmission (trade) between farms, and (iv) the introduction of new animals into the population. We assume that (1) recovery from natural BVD infection leads to lifelong immunity, that (2) calves with maternal antibodies are protected for about 6–9 months after birth and that (3) vaccination requires yearly boosting. To take the constant risk of disease introduction through imports into account, the model includes a trade manager and the PI prevalence of imported animals was set at 2%. Each individual animal is simulated from birth to death.

The following input parameters were retrieved from the DSM:

- Number of farms with no active infection (i.e., all animals susceptible), with protected (recovered or vaccinated) animals, and with PI animals per scenario and year;
- Number of PIs and TIs and animals that died from mucosal disease per scenario and year;
- Number of farms and animals subject to control measures, i.e., number of diagnostic tests (ear tag, blood samples for PCR and AbT), scenario and year; number of vaccinated animals and number of vaccinations by scenario and year;

The following values from the German cattle trade database (HIT) were used as input parameters: Number of farms and farm size distribution, age distribution for males and females, cause of death, age at first calving, calving interval, BVD test results, and number of PIs and TIs between 2010 and 2017.

The simulation was run in C++ for the years 1983–2030 (total of 20,000 days). Thereof, the first 10,000 days were used to reach a stable state in disease dynamics. After 5,000 days an equilibrium between susceptible, recovered, PI and TI animals was reached. The source code of the model can be accessed in a repository (https://github.com/Yperidis/bvd_agent_based_model). The disease spread model is described according to Grimm et al. (28) and can be found at arXiv (29). Further details on the model and its validation can be found at Bassett (30). Since our statistical software is not equipped to handle extremely large datasets (12.4 million head of cattle, 13 different scenarios), we first run the model on a subset of 360,000 animals. We then scaled the results up to the whole cattle population in Germany using a factor of 39.2.

Gross Margin Analysis (GMA)

To estimate the effects of a transient BVD infection in terms of production losses, a gross margin analysis (GMA) on animal level was performed for dairy cows and heifers. To consider the heterogeneity of cattle farms in Germany in terms of herd size and management, the GMA was performed as a stochastic model. All estimations are based on data of the German Association for Technology and Structures in Agriculture ("*Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V., KTBL*"), the animal health services ("*Tiergesundheitsdienste*"), animal disease compensation funds of the federal states ("*Tierseuchenkassen*"), Destatis, and HIT database (**Table S1**). The GMA was carried out with R statistical software (31) and the packages *xlsx, ggplot2, sm, fitdistrplus, MASS, foreign, EnvStats, stats, graphics, utils,* and *base*. For each set of parameters, 10,000 iterations were conducted.

We calculated the gross margin (GM) for both, healthy animals (GM_h), i.e., in absence of BVD, and for cattle with a transient BVD infection (GM_{TI}) by adapting the respective variables for the calving interval, milk yield, and veterinary costs. Direct costs incurred by a TI animal (DC_{TI}) were then calculated as the difference between both:

$$DC_{TI} = GM_h - GM_{TI}$$

To quantify the average impact of TI on reproduction, we used the calving interval (Ci). In case of BVD induced abortion/stillbirth, the Ci was increased by a certain number of days.

To quantify these, we first estimated the probability of the outcome (abortion/stillbirth) on five different time periods, including four pregnancy stages (days 1–70; 71–120; 121–180; 181–285) and the post-partum stage (days 286–385), based on Viet (32). We then calculated the overall probability for an animal being in a particular stage with a specific outcome (birth of a PI calf, abortion/stillbirth, congenital defect/growth retardation, birth of an immune calf, no influence; **Table S5**). Finally, we estimated the number of days the "healthy" Ci had been prolonged in each stage, as the average of the respective period (**Table S6**).

To quantify the impact of TI on the revenues in milk sale, we multiplied the difference between the milk yield of a "healthy" and that of an infected cow with the average milk price. All equations and input parameters are shown in **Table S1**.

Animal Valuation Model (AVM)

To estimate the market value (v_c) of PI animals that prematurely die of BVD, we devised a stochastic animal valuation model (AVM) based on the appraisal guidelines of the animal health compensation fund of North-Rhine-Westphalia governing indemnity payments for livestock ("*Schätzrahmen*"). Two different equations were used (for dairy cows as well as calves and young stock, respectively). The equations combine the age of the animal (in months) with production, reproduction and animal health data (**Table S2**). The AVM was carried out using R statistical software (31) using the packages *xlsx, pander, ggplot2, sm, fitdistrplus, MASS, foreign, EnvStats, stats, graphics, utils,* and *base*.

Economic Model

To simulate the economic impact of BVD and the control measures on national level, we developed a stochastic economic model in @Risk for Microsoft Excel 2010 with 20,000 iterations, covering a period of 20 years (2011–2030). For parametrization, the results of the DSM, GMA, and AVM were used. For all other parameters, we used empirical distributions based on literature and expert opinion (Horst Schirrmeier, Kerstin Wernike, and Martin Beer from the FLI, Georg Wolf from the Ludwig-Maximilians-Universität München, and Karsten Donat from the animal disease compensation fund Thüringen). All parameters and equations are listed in **Tables S3, S4**. We differentiated between four different age groups: calves (1–6 months), young stock (7–18 months), heifers (females 19–28 months), and cows (females >28 months).

Total costs of BVD

The total costs of each scenario for the 20-year study period (2011–2030) include direct and indirect costs.

Direct costs PIs. If not discovered in time, PIs may display clinical symptoms thus requiring veterinary treatment, and they usually die within the first 2 years of life (33). Hence, the direct costs incurred by a PI animal include veterinary costs and costs incurred through premature death. The latter include the disposal costs for a calf, young stock or cow, and the lost market value of the animal (calculated in the animal valuation model, see chapter 3.2.3). The costs of culling or preventive slaughter were included in the indirect costs (as they represent a BVD control measure).

Direct costs Tis. Transient infection with BVD may cause production losses in all age groups. In calves and young stock, losses include poor growth and weight loss, and were estimated using a risk uniform distribution (**Table S1**). For heifers, losses include increased calving interval and were estimated in the GMA for heifers (**Table S1**). For cows, losses include increased calving interval (Ci) and the reduced milk yield. They were estimated in the GMA for cows (**Table S1**). For heifers and cows, we took a sample from the GMA results using the RiskResample function in @Risk.

Indirect costs of BVD. Depending on the scenario, the indirect costs of BVD include the costs to prevent infection, i.e., diagnostic measures and vaccination, as well as costs to control the disease, including culling or preventive slaughter of PIs and trade restrictions.

Diagnostic measures: Individual BVD diagnosis can either be done through antigen or BVDV genome detection (tissue sampling by ear tag in calves or blood sampling in adults) or AbT (blood sampling in young stock). Ear tags are applied by the farmer. Hence, the costs for antigen detection in ear tags include material (ear tags and a certain percentage of ear tag pliers) and labor (shipping, testing and communicating test results). In contrast to tissue samples, blood samples need to be taken by a veterinarian. So at individual animal level, the costs for antigen detection in blood include the costs for blood sampling and testing (PCR). On the farm level, the costs include the herd fee, handling, shipping, and communicating test results. Similar to blood sampling for antigen detection, the costs for blood sampling for AbT include on the farm level the herd fee, handling, shipping, and communicating results. At the individual animal level, they include costs for sampling and testing (ELISA).

Vaccination: In all six scenarios that include vaccination (sc5, 8, 9, 11, 12, 13), vaccination was planned to be compulsory for all female animals before getting pregnant. In the remaining seven scenarios, vaccination was not included. Depending on the vaccination scheme, several immunizations are required. As vaccines must only be administered by veterinarians in Germany, vaccination costs include the herd fee charged by the veterinarian. At the individual animal level, we accounted for the number of immunizations per animal and the costs for the vaccine and vaccination.

Preventive slaughter of PIs: Usually, PIs are culled or preventively slaughtered as soon as they are discovered. The lost revenues and costs were calculated by multiplying the number of preventively slaughtered PI calves, young stock and cows by their relative market value, which was assumed to be lower than the value of an average slaughter animal.

Trade restrictions: If a BVD infected animal is detected, cattle must not be moved from the affected premise for 40 days according to national legislation. Non-pregnant cattle can only leave the farm for slaughter or if the animal has been subjected to a second test 40 days after the initial analysis at the latest. Pregnant cattle may be moved if the animal has been subjected to a serological test after the 150th day of gestation with a negative result. We assumed that each affected farm would move three pregnant and three non-pregnant dams within 40 days of quarantine (34). This implies the following costs for these three pregnant and three non-pregnant animals: travel 10 €, taking blood samples 10 €, handling and shipping samples 9 €, laboratory analysis 30 € (3 × 10 €). Hence, the movement ban would result in 118 € (2 × 59 €) additional veterinary costs per affected premise.

Cost-benefit analysis

A cost-benefit analysis (CBA) was conducted to evaluate the profitability of each scenario compared with sc1 (no BVD control) throughout the study period (2011–2030). The CBA was performed as described by Rushton et al. (35). It was conducted as a stochastic simulation with the add-on @Risk 5.7 (Palisade Corporation, Ithaca, NY, USA), performed with 10,000 iterations. The built-in @Risk sensitivity analysis tool was used to evaluate which input parameters had the strongest effect on the results. The benefit-cost ratio of each scenario (BCR_s) was calculated by dividing the present value of benefits (PVB_s) by the present value of indirect costs ($PVIC_s$).

$$BCR_s = \frac{PVB_s}{PVIC_s}$$

PVB and PVIC were calculated as follows (where r is the interest rate):

$$PVB_s = \sum_{y=2011}^{2030} \frac{B_{y,s}}{(1+r)^{(y-2011)}}$$

$$PVIC_s = \sum_{y=2011}^{2030} \frac{IC_{y,s}}{(1+r)^{(y-2011)}}$$

The annual benefit ($B_{y,s}$) of each scenario was calculated as the difference in disease (i.e., direct) costs between sc1 ($DC_{y,s1}$) and the respective alternative scenario x ($DC_{y,s}$).

$$B_{y,s} = DC_{y,s1} - DC_{y,s}$$

All monetary values were expressed in Euros. Break-even points (the point at which total cost and total revenue are equal) were obtained from the annual results for each scenario. The analytical objective of this part of the study was to estimate the net present value (NPV) of different scenarios over the study period of 20 years. To enable a comparison between past, current and future values, all monetary flows for the benefits and costs were discounted at a rate of 3%. For reasons of comparability, foreign currencies referred to in the international literature were converted into Euros using the average currency exchange rate valid in the year of publication of the respective study.

RESULTS

Disease Spread Model

The results of the DSM have been described elsewhere (30). According to the DSM, only scenarios that combine antigen or antibody testing with compulsory vaccination (sc5, sc8, sc9, sc13) are likely to reduce the PI prevalence on animal level to 0%, i.e., may lead to the eradication of BVD (**Figure 1**). In sc5, the PI prevalence will reach 0% in the third quarter of 2022, in sc8 and sc9 in the fourth quarter of 2022, and in sc13 in the second quarter of 2023. In scenarios that include compulsory vaccination, the prevalence of protected animals (recovered or vaccinated) will be above 75% by 2030. Scenarios that include antigen testing (sc2, sc3, sc6, sc7) may reduce the PI prevalence to a value 0.01%. All other scenarios, including the control program currently in place, are unlikely to lead to BVD eradication. In scenarios sc4, sc10, sc11, and sc12, the PI prevalence is predicted to stay in the range of 0.01–0.05% by 2030. In scenario sc1, the PI prevalence will decrease gradually from 1.2 to 0.9% and the seroprevalence (recovered animals) will go down from 64 to 47%,

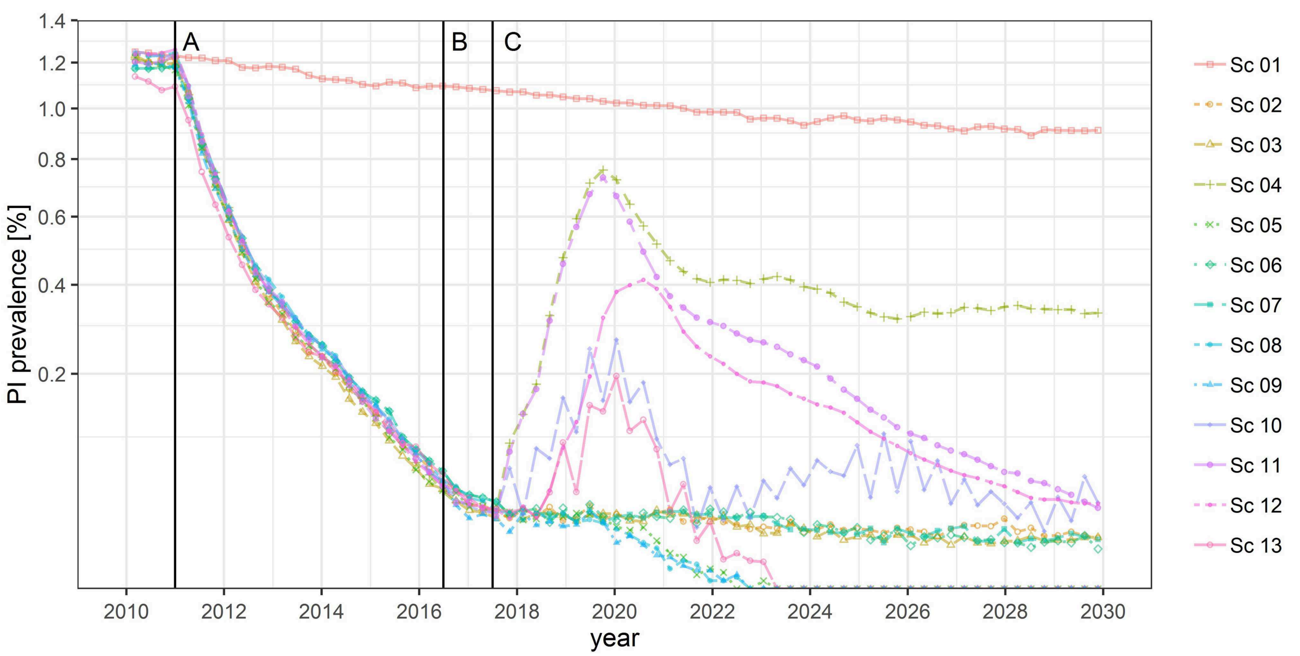

FIGURE 1 | Predicted PI prevalence between 2010 and 2030 for each BVD scenario. **(A)** Start of the former BVD regulation (sc2). **(B)** Start of new BVD regulation (sc3). **(C)** Start of alternative scenarios (sc4–sc13).

while the proportion of susceptible animals will increase from 35 to 52% and the TI prevalence is predicted to stay nearly constant at a level of 0.25–0.33%.

As soon as testing stops in scenario sc4, the PI prevalence will rapidly rise up to 0.75% in 2019 and is predicted to decrease then again, but a proportion of 0.33% PI animals will still remain by 2030 (**Figure 1**, **Table 2**). Although scenarios sc11 and sc12 include vaccination, they do not combine it with testing, and will not lead to BVD eradication according to the model predictions. In all other scenarios, the prevalence of protected animals will be 3–7% by 2030.

Gross Margin Analysis

In cows, the direct costs of a transient infection were estimated at 55.71 Euros per animal on average (**Figure 2A**). An increased Ci of 0–60 days increased the direct costs by 0–180 Euros (**Figure 2B**). A reduced milk yield of 64–76 L reduced the GM in average by 50 Euros (**Figure 2C**). In heifers, the average costs were estimated at 7.80 Euros, and for calves and young cattle between 0 and 10 Euros (mean 5 Euros).

Animal Valuation Model

The results of the AVM are shown in **Table 3**. The mean value of a cow was estimated at 1,451 Euros (**Table 3**).

Economic Model

The results of the economic model are listed in **Table S7** (direct, indirect, and total costs per year). Direct costs are estimated at 113 (34–402) million Euros per year. They are predicted to stay nearly constant over time, since the PI prevalence decreases very slowly. **Table 4** details the minimum, maximum, and mean total costs. The total costs arising from BVD in sc1 (no BVD control) were estimated at 2.258 billion Euros. The least expensive scenarios among those that continue with BVD control are sc12 and sc11 (stop testing and switch to vaccination, either gradually or immediately), followed by sc3 (ear tag and quarantine), and sc2 (ear tag). Scenarios sc11 and sc12 generate total costs of 1.81 and 1.77 billion Euros, respectively. Similar to scenario sc4, the majority of costs are predicted to arise in the initial years, while from 2023 onwards both scenarios, sc11 and sc12, will become cheaper until they are expected to level off at about 65 and 66 million Euros per year. Sc2 and sc3 are predicted to cause total costs of 1.93 and 1.91 billion Euros, respectively. The costs of both scenarios will level off from 2017 onwards and lead to nearly constant sums of about 84 and 82 million Euros per year.

Seven scenarios are predicted to be more expensive than sc1. The five most expensive scenarios all include AbT. With total costs of 7.23 billion Euros, the most expensive scenario will be sc8 (ear tag, AbT twice a year and vaccination). From 2017 onwards, sc8 is predicted to generate increasing costs until 2024, and from 2024 onwards, they will level off at 538 million Euros per year. As the PI prevalence is predicted to decrease to almost 0%, all costs are allocated to control measures, in particular antigen testing in blood (72%), antigen testing in ear tags (13%), vaccination (11%), and antibody testing (4%) (**Figure 3**).

The second most expensive scenario is sc6 (ear tag and AbT twice a year), which is predicted to generate total costs of 3.65 billion Euros, of which 90% (3.30 billion) are allocated to disease control. The costs of sc6, sc10, and sc7 peak in 2018 and then almost constantly decrease until 2030. Scenario sc13 (AbT twice a year, vaccination) is the third most expensive scenario and is expected to generate 2.75 billion Euros costs (thereof 88% for disease control), followed by sc9 (ear tag, AbT once a year, vaccination, 2.7 billion Euros), sc10 (AbT twice a year, 2.68 billion Euros), sc5 (ear tag, vaccination, 2.53 billion Euros), and sc7 (ear tag, AbT one a year, 2.51 billion Euros).

Toward the end of the study period, the yearly costs of all scenarios are predicted to level off at almost constant sums: The cheapest scenario will again be scenario sc4 (36% of sc1), followed by sc12, sc11, sc3, and sc2 (66–80% of sc1). Scenarios sc7 and sc10 will be slightly more expensive (103–104% of sc1), followed by sc5, sc9, sc13, and sc6 (138–171% of sc1), and sc8 is expected to stay the most expensive scenario (535% of sc1).

The highest disease impact is predicted to occur in sc1 and sc4, i.e., in scenarios with no control or stopping control measures altogether (2.26 billion Euros, 100% of the total costs of sc1, and 845 million Euros, 60% of the total costs of sc4). Among the scenarios with control, the highest disease impact is predicted to occur in sc11 and sc12 (584 and 473 million Euros, 32 and 27% of the total costs, respectively), followed by sc10 (427 million Euros, 16%) and sc2, sc6, sc7, sc3, and sc13 (360–324 million Euros, 10–19%). The lowest disease impact is expected to occur in sc5, sc8, and sc9 (280–285 million Euros, 4–11% of the total costs). All estimates are reported as medians.

Sensitivity analysis showed that the costs for AbT had the highest impact on the indirect costs. In scenarios without vaccination (sc6, sc7, sc10), the number of AbT will stay constant (∼2.8 million tests per year for sc6 and sc10 and 1.4 million tests per year for sc7). On the other hand, the number of positive AbT is predicted to decrease to about 8% in scenarios sc6 and sc7, and to 12% in scenario sc10. In scenarios with vaccination (sc8, sc9, and sc13), the number of AbT will first decrease and

TABLE 2 | Prevalence of PI and BVD antibody-positive animals (recovered or vaccinated).

Scenarios	Prevalence in 2030 (%)	
	PIs	Antibody positive animals
Scenario 01	0.894	46.91
Scenario 02	0.010	4.36
Scenario 03	0.009	3.17
Scenario 04	0.317	18.93
Scenario 05*	0.000	75.49
Scenario 06	0.011	3.49
Scenario 07	0.010	3.82
Scenario 08*	0.000	75.59
Scenario 09*	0.000	75.61
Scenario 10	0.053	6.53
Scenario 11*	0.026	75.95
Scenario 12*	0.026	75.98
Scenario 13*	0.000	75.62

Scenarios that include vaccination are marked with an asterisk (*).

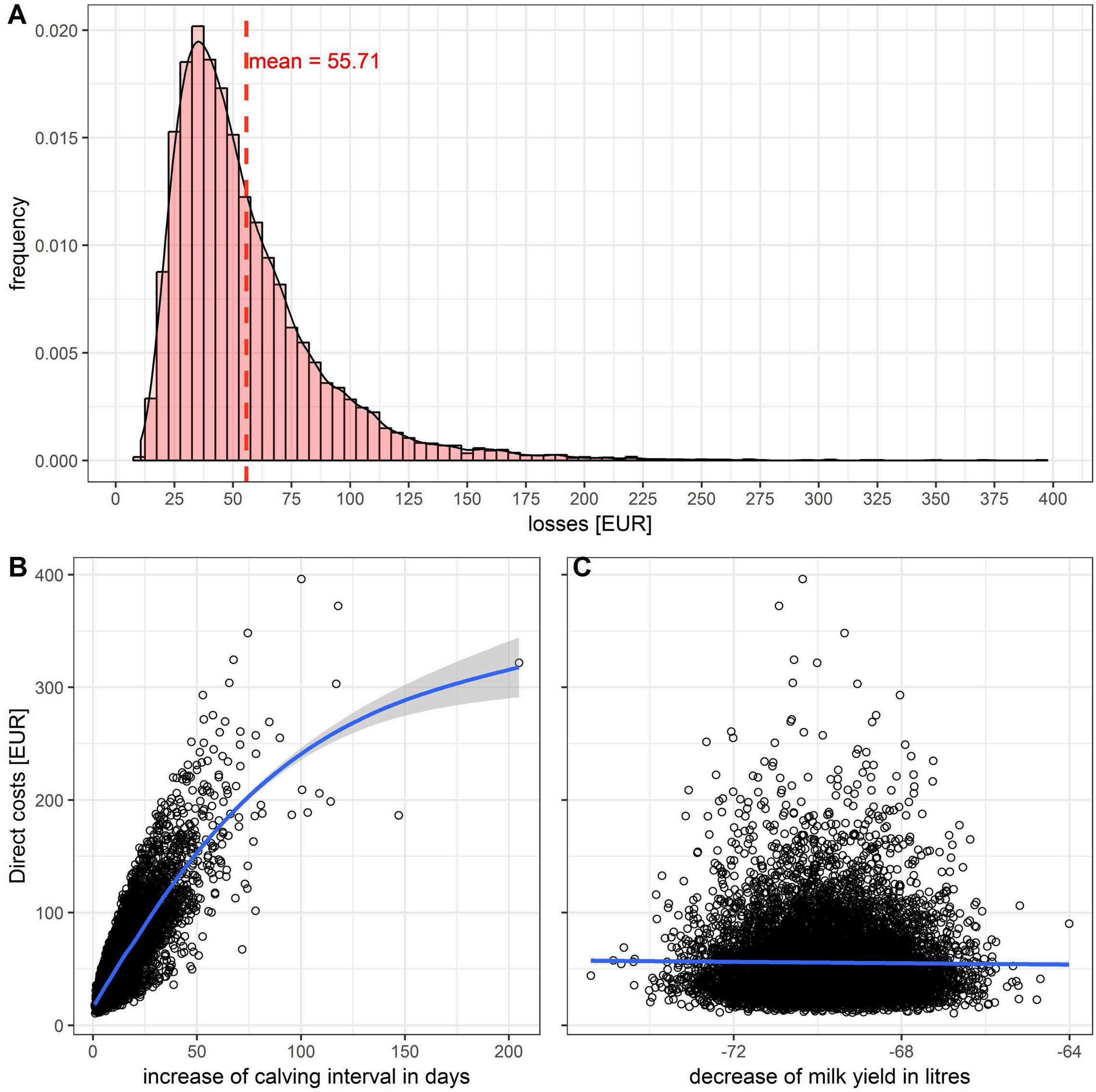

FIGURE 2 | Impact of a transient BVD infection in a dairy cow: **(A)** Histogram of the total losses. **(B)** Influence of the increased calving interval. **(C)** Influence of the decreased milk yield on the losses.

stay constant from 2023 onwards (∼475.000–946.000 tests per year). In scenarios with vaccination (sc8, sc9, sc13), the number of BVD antibody-positive animals will remain in the range of 132,000–265,000 from 2022 onwards.

Compared to sc1, the break-even points of all scenarios were estimated to be reached in 2017. However, only sc2, sc3, sc4, sc11, and sc12 are predicted to stay beneficial, while the cumulative costs of all other scenarios will rise in the following years and will finally be higher than the benefit. Scenarios sc6, sc7, sc8, and sc10 are unlikely to result in profit from 2018 onwards, sc9 from 2021, sc13 from 2022, and sc5 from 2023 onwards.

Table 5 lists the undiscounted and discounted benefit (B), indirect costs (IC), benefit-cost ratio (BCR), net value (NV), and net present value (NPV) per scenario.

The discounted BCR was estimated to range between 0.31 (sc8) and 2.08 (sc4). It was >1 for scenarios sc2, sc3, sc4, sc11, and sc12. This means in case of scenario sc4, that 2.08 Euros are saved for each invested Euro, whereas only 0.31 Euros per invested Euro are saved in scenario sc8.

DISCUSSION

We developed two models (DSM and an economic model) to plan, evaluate, and improve BVD control programs. The models were applied to the situation in Germany, a country that is currently in the process of optimizing its BVD control strategy. Both models may also be applied in other countries. They can help to design or improve other disease control

TABLE 3 | Estimated market value of cattle of different age classes.

	Calves (0–6 months)		Young stock (7–24 months)		Heifers						Cows
Age in months	**1**	**...**	**12**	**...**	**24**	**25**	**26**	**27**	**28**	**29**	
Mean	304.4	...	902.3	...	1,616.8	1,673.4	1,729.9	1,855.1	1,913.9	1,972.6	1,451.4
Min	165.1	...	489.3	...	876.7	907.4	938.0	1,005.9	1,037.8	1,069.6	376.9
1st Qu	276.6	...	819.9	...	1,469.1	1,520.5	1,571.9	1,685.7	1,739.0	1,792.4	1,260.8
Median	316.2	...	937.4	...	1,679.7	1,738.4	1,797.1	1,927.2	1,988.2	2,049.2	1,493.8
3rd Qu	339.8	...	1,007.4	...	1,805.0	1,868.1	1,931.2	2,071.0	2,136.6	2,202.1	1,682.6
Max	358.6	...	1,062.9	...	1,904.5	1,971.1	2,037.7	2,185.2	2,254.4	2,323.5	1,936.3

TABLE 4 | Total costs (direct and indirect costs) per scenario (million Euros) with minimum and maximum values.

Scenario	Mean	Minimum	Maximum
sc1	2,258	1,821	3,497
sc2	1,933	1,614	2,540
sc3	1,909	1,602	2,469
sc4	1,413	1,162	2,195
sc5	2,525	2,167	3,139
sc6	3,655	2,966	4,520
sc7	2,511	2,122	3,214
sc8	7,229	5,567	9,128
sc9	2,703	2,308	3,287
sc10	2,680	2,094	3,488
sc11	1,812	1,503	2,402
sc12	1,769	1,430	2,534
sc13	2,747	2,206	3,498

programs and to avoid problems that may be expected in their course.

Economic Model

We estimated the direct costs of BVD to range from 34 to 402 million Euros per year in Germany, with a mean of 113 million Euros, corresponding to 28.3 million Euros per million animals. These results fall within the range of estimates that were previously obtained for other countries. Projected on costs per million animals, direct BVD costs were estimated at 18–21 million Euros for Switzerland (36), at 16.3 million Euros for Norway (37), at 10.3–28 million Euros for the Netherlands (15), and between 32 million (suckler cows) and 63 million Euros (dairy cows) for Ireland (38). High costs associated with BVD infection has led to increased disease in the cattle industry and to public eradication efforts. Although the German program has been regarded as successful in recent years (23), it is currently under revision as eradication has not yet been achieved.

All scenarios that include only "test and cull" strategies, i.e., also the current control program, are unlikely to have eradicated BVD in Germany by 2030. Only scenarios that combine either antigen or antibody testing with compulsory vaccination (sc5, 8, 9, 13) are likely to reduce the PI prevalence to 0% according to the model predictions. However, from an economic perspective, these scenarios are not beneficial.

Scenarios that combine antibody and ear tag testing (sc6, 7, 8, 9) may result in a significantly faster decrease of PI prevalence, but none of them is economically attractive due to the large numbers of tests required for surveillance. Scenario sc10 (AbT only) leads to an increase in PI prevalence and causes higher costs than sc1. In this case, risk-based surveillance may reduce the number of samples, while providing a high sensitivity at the same time (36). Risk-based categorization of farms could be performed by taking for example the number of animal movements and the disease status of the origin of purchased animals into account.

Of all simulated scenarios, only four were found to be economically attractive, namely scenarios sc2, sc3, sc11, and sc12, with an NPV of 222, 238, 307, or 337 million Euros, respectively. Although scenario sc4 has an NPV of 572 million Euros, it must be assumed that the disease costs will rapidly increase again if all control measures are abandoned. With scenarios sc11 and 12 (vaccination only), eradication does not appear to be feasible. If BVD control is stopped before the last PI is removed (see sc4), the PI prevalence is predicted to level off on the long term at about 0.33%. Previous studies do not advise premature discontinuation of control efforts, as a mainly seronegative cattle population is fully susceptible to BVD (39). Abandoning the long-standing goal of eradicating BVD may lead to necessity of imposing trade restrictions and, more importantly, to the loss of credibility of official disease eradication programs.

In summary, scenarios sc2 and sc3 were predicted to be successful in terms of both, disease eradication and benefit-cost ratio. However, a major current challenge for BVD eradication is the unrecognized import of inapparent or subclinical PI animals. A recent risk assessment showed that BVD is regularly introduced in the Netherlands through cattle importations and estimated that 334 cattle herds may become infected per year (40).

According to our results, the control program currently implemented in Germany is beneficial (BCR = 1.2). This is in line with calculations for Ireland (38) and Switzerland (36), which run similar control programs as Germany. Both groups calculated a higher BCR (10 and 1.9) than we did. In the Netherlands (15), where a control program based on bulk milk testing is in place, the BCR = 1.5 is slightly higher than the one we calculated for Germany. Other studies came to a negative BCR, e.g., for Styria, Austria, with a BCR of 0.83 (41). Comparing our results directly with those of others is difficult as the control programs are different, the assessment periods vary in

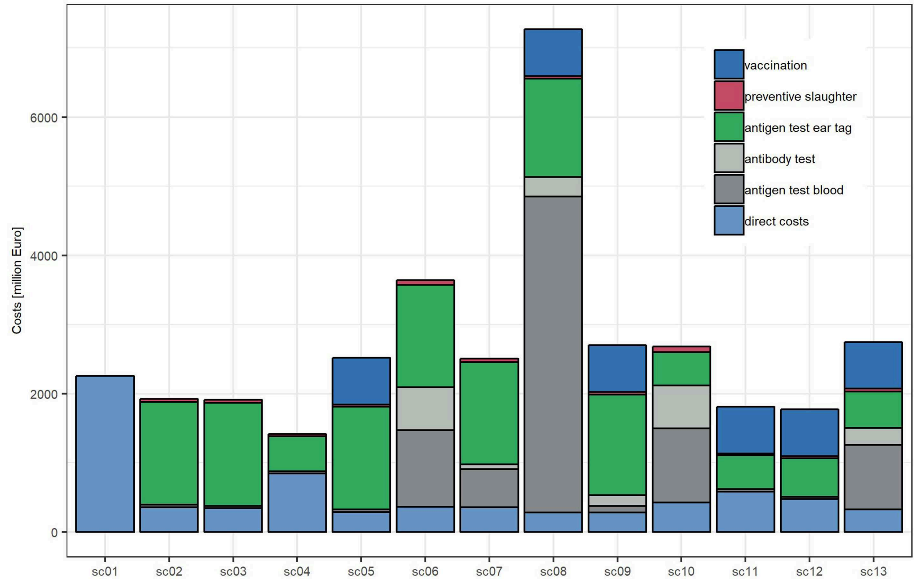

FIGURE 3 | Direct and indirect costs incurred 2011–2030 in the 13 simulated scenarios.

TABLE 5 | (A) Undiscounted and (B) discounted benefit (B/PVB), indirect cost (IC/PVIC), benefit-cost ratio (BCR), and net value (NV/NPV) of the 13 simulated scenarios (in million Euros).

Scenario	(A) Undiscounted				(B) Discounted			
	B	IC	BCR	NV	PVB	PVIC	BCR	NPV
sc1								
sc2	1.897	1.573	1,22	324	1.437	1.216	1,18	222
sc3	1.915	1.566	1,24	349	1.449	1.211	1,2	238
sc4	1.413	569	1,1	844	1.097	524	2,09	572
sc5	1.972	2.240	0,92	−268	1.488	1.658	0,9	−170
sc6	1.898	3.295	0,69	−1.397	1.437	2.433	0,59	−996
sc7	1.901	2.154	0,92	−253	1.439	1.633	0,88	−193
sc8	1.976	6.947	0,52	−4.971	1.491	4.837	0,31	−3.346
sc9	1.978	2.423	0,87	−445	1.492	1.785	0,84	−293
sc10	1.831	2.253	0,93	−423	1.388	1.710	0,81	−322
sc11	1.674	1.229	1,95	445	1.266	959	1,32	307
sc12	1.785	1.296	1,51	489	1.351	1.014	1,33	337
sc13	1.934	2.424	0,94	−490	1.458	1.772	0,82	−314

The discounting rate is 3%.

time and duration, and the cattle structure (e.g., herd structure, trade patterns and animal density) may not be comparable. A recent review has only identified four countries (Norway, Ireland, France and Switzerland), where the implementation of BVD mitigation activities appeared economically justified after a specific period (16).

Disease Spread Model

In scenario sc1, BVD reaches an endemic status with a PI prevalence of at least 0.9%. Over the study period, the PI prevalence was predicted to decrease slightly and no steady state was reached within the projected period, although the rate of reduction was very small. Most probably, this is due to fact that the disease transmission rates between animals and farms were estimated rather low, although they were based on values obtained from literature (32).

In scenario sc4, we observed a rapid increase of the PI prevalence up to 0.75% just after stopping BVD control, before it decreases and levels off at about 0.33%. The initial increase of the PI prevalence is due to the high number of naïve animals at the end of the control program. In the following years, the number of animals recovered from transient infection increases and the number of PI animals decreases until a steady state is reached. In contrast to sc1, the PI prevalence is lower, probably because in sc1 no steady state is reached.

Compared to real life data, the initial PI prevalence in the DSM was three times higher (1.2 vs. 0.4%) (**Figure 4**). To explain this phenomenon, it has to be taken into account that (i) reliable data from the HIT database were not available until mid-2011 and (ii) in reality, several federal states had already implemented different types of voluntary control programs in 2011. Hence, the reported prevalence at the animal and farm level in previous years does not necessarily reflect a baseline scenario (without BVD control), but rather a heterogeneous situation. Compared with studies carried out prior the start of any control program, e.g., 2.1% in Lower Saxony, Germany (42) or 0.8–1.3% in Switzerland (9, 11, 43), the assumed PI prevalence of 1.2% in the DSM seems realistic.

Previous studies revealed BVD seroprevalences of 64–97% in Germany (44), 57.6% in Switzerland (45), and 33–54% in Belgium (46, 47). Compared with these studies, the antibody prevalence of 47% in the DSM seems to be realistic.

Compared with real data obtained from the HIT database, the reduction in PI prevalence seems to be predicted in a rather realistic fashion by scenario sc3, with the only difference that the PI prevalence was reduced to 0.01% in the first quarter of 2017 in reality, while this prevalence level will not be reached until 2024 according to the model prediction (**Figure 4**). This may be due to the fact that (i) the initial PI prevalence in scenario sc3 is three times higher than in reality, and (ii) we did not simulate further effects in the DSM, e.g., additional measures carried out by the farmers.

Scenarios that include only ear tag testing (sc2, sc3), only AbT (sc10) or a combination of both (sc6, sc7) will not lead to BVD eradication. Regarding scenarios sc2 and sc3, the reasons are imperfect tests, the continuous importation of PI animals, delayed removal of PI animals, and failure to take transient infections into account (23).

In scenario sc10, the number of PI animals increased after switching from ear tag to antibody testing only. This confirms experiences made in Switzerland in 2012/2013 (https://www.infosm.blv.admin.ch/public/). Hence, in terms of PI prevalence, this option is worse compared to ear tag testing (sc2, 3) Only scenarios that combine vaccination with either ear tag (sc5) or AbT (sc13) or both (sc8, sc9) are expected to lead to eradication according the modeling results. All scenarios that include AbT are predicted to lead to an unexpectedly high number of blood antigen tests. This is due to the fact, that, according to German BVD regulation, all cattle in a farm are subjected to a virus isolation test to detect viremic animals if an animal is confirmed antibody positive. Furthermore, maternal BVD antibody titers are still high enough to be detectable in calves until the age of 9 months. This can explain why so many animals (tested at the age of 7–18 months) were antibody positive in the DSM and why strategies that include AbT are so effective in reducing the PI prevalence. However, in reality, the number of antigen tests may be substantially lower, probably because animals subjected to AbT are older than 7 months. Moreover, it seems unlikely that all animals of a farm will be tested if a single BVD-positive result is obtained in this herd.

Other studies on the spread of BVD and the effect of different control strategies were published for Scotland (48), Ireland (49), and Italy (50). Nevertheless, the authors used other approaches to model disease spread or tested different control strategies. Tinsley

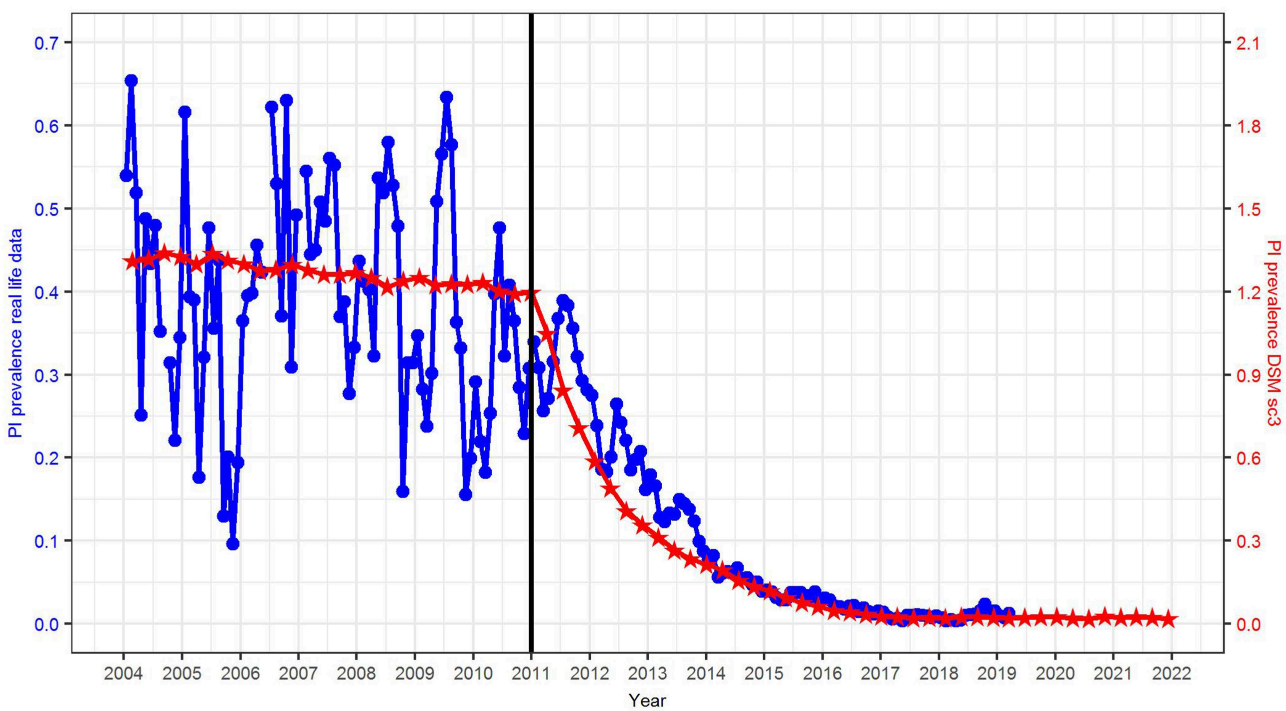

FIGURE 4 | Comparison of the PI prevalence in reality (source: HIT, blue circles, left axis) and simulated in the DSM, scenario sc3 (red stars, right axis).

et al. (48) compared only trade restrictions, using a network model. Thulke et al. (49) tested the change from the current control system (ear tag testing), which is similar to the German strategy, to serological testing. They also included additional factors, e.g., difficulties in changing the strategy. Iotti et al. (50) used a more general approach in analyzing a random or targeted removal of farms from the network. These models and the results obtained with them can therefore not be compared directly with our findings.

Gross Margin Analysis

The sensitivity analysis showed that the economic model was most sensitive to alterations in the parameters associated with production losses. The GMA revealed a mean economic impact of 56 Euros per TI dairy cow, 8 Euros per heifer and 5 Euros per calf and thus falls within the range of previous studies: Two worldwide reviews quote the economic impact of BVD as 0.4–585 Euros (1) or 0–621 Euros per animal (2). Losses per cow and year were estimated at 56-133 Euros for France (51), 9.2 Euros for Norway (37) and 75.5–79.1 Euros for Switzerland (14). In Bavaria, losses were estimated at 40 Euros per TI in a lactating cow, 25 Euros per TI in a non-lactating cow and 25 Euros per young stock or heifer (52). In the Netherlands, the production losses per milking cow due to BVD were estimated to range from 19 to 384 Euros per milking cow, with 72 Euros as the most likely value (53). However, these costs included a biannual vaccination of all cows in the herd against BVD and further actions that had to be taken by a farmer to obtain a BVD-free status for the herd. In general, reproduction losses associated with BVD may vary greatly and it is difficult to compare them for different population sizes, herd, and animal-specific conditions and periods.

Limitations

The disease spread model (DSM) was designed to model the disease spread via animal trade. Each farm can sell and buy from all other farm, which might promote the spread of the virus and thus lead to an overestimation of the number of affected farms. Also, the model simulates the continuous influx of a certain proportion of PI (2% of imported animals). The assumed influx represents a worst-case scenario, which may not necessarily reflect the true current situation. However, Germany is not entitled to additional guarantees of BVD-freedom if cattle are imported from other EU member states, so an influx of PI animals through cattle trade with farmers in other EU member states is possible. If and when Germany may achieve freedom from BVD with a smaller number of imported PI animals will have to be analyzed in a future study. Moreover, virus spread by people (e.g., animal traders, veterinarians, farmers) is not taken into account in the model, which might lead to an underestimation of the PI incidence. We also had to make some simplifications in the model: We did not consider different (combinations of) BVD vaccines, but simulated only the use of a single vaccine with "standard" efficacy. We also assumed that PI calves do not receive maternal antibodies. This should have no influence on the model, since there was only a small number of PI calves. On the other hand, serological testing of calves with maternal antibodies leads to false-positive test results and consequently to the virological testing of the whole herd with a consequence of a massive overestimation of the number of tests.

A sensitivity analysis was carried out for several parameters, e.g., population size, transmission rate, time lag until retesting, vaccination efficacy (29, 30). When we compared the output of the model with the data available from the German cattle trade database, we observed similar trade patterns and age distributions. Socio-economic or animal welfare aspects as well as trade benefits that may arise from a BVDV-free status as well as possible future developments in European legislation on BVD control were beyond the scope of this study. Increased biosecurity in terms of quarantine in combination with testing imported animals in quarantine in the farm of destination may decrease the risk of virus spread. The PI prevalence might be reduced accordingly in all scenarios that include control measures. However, enhanced biosecurity measures were not taken into account in our model.

In conclusion, we modeled the spread of BVDV with and without control measures and calculated the economic impact of the disease and its control using data from Germany. Our analysis showed that within the given limitations, only scenarios with a combination of testing and compulsory vaccination will lead to eradication. However, these scenarios are not beneficial from an economic perspective. The currently implemented eradication program is likely to reduce the PI prevalence to a very low value close to 0 % at a reasonable cost-benefit ratio.

AUTHOR CONTRIBUTIONS

JG, FC, and CP contributed conception and design of the study. JG, PB, JB, and PH developed the agent-based model. JG, CP, and FC developed and run the gross margin analysis. JG developed the animal valuation model (AVM). JG and CP developed the economic model. CP and JG wrote the first draft of the manuscript. All authors contributed to 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.2019.00406/full#supplementary-material

REFERENCES

1. Richter V, Lebl K, Baumgartner W, Obritzhauser W, Kasbohrer A, Pinior B. A systematic worldwide review of the direct monetary losses in cattle due to bovine viral diarrhoea virus infection. *Vet J.* (2017) 220:80–7. doi: 10.1016/j.tvjl.2017.01.005
2. Yarnall MJ, Thrusfield MV. Engaging veterinarians and farmers in eradicating bovine viral diarrhoea: a systematic review of economic impact. *Vet Rec.* (2017) 181:347. doi: 10.1136/vr.104370
3. Houe H. Economic impact of BVDV infection in dairies. *Biologicals.* (2003) 31:137–43. doi: 10.1016/S1045-1056(03)00030-7
4. King AMQ, Lefkowitz EJ, Mushegian AR, Adams MJ, Dutilh BE, Gorbalenya AE, et al. Changes to taxonomy and the International Code of Virus Classification and Nomenclature ratified by the International Committee on Taxonomy of Viruses 2018. *Arch Virol.* (2018) 163:2601–31. doi: 10.1007/s00705-018-3847-1
5. Gethmann J, Homeier T, Holsteg M, Schirrmeier H, Saßerath M, Hoffmann B, et al. BVD-2 outbreak leads to high losses in cattle farms in western Germany. *Heliyon.* (2015) 1:e00019. doi: 10.1016/j.heliyon.2015.e00019
6. Larghi M. Comparative study in the control of bovine viral diarrhea. *Anim Health Res Rev.* (2018) 19:125–33. doi: 10.1017/S1466252318000129
7. Richter V, Kattwinkel E, Firth CL, Marschik T, Dangelmaier M, Trauffler M, et al. Mapping the global prevalence of bovine viral diarrhoea virus infection and its associated mitigation programmes. *Vet Rec.* (2019) 184:711. doi: 10.1136/vr.105354
8. Moennig V, Becher P. Control of bovine viral diarrhea. *Pathogens.* (2018) 7:29. doi: 10.3390/pathogens7010029
9. Presi P, Heim D. BVD eradication in Switzerland-a new approach. *Vet Microbiol.* (2010) 142:137–42. doi: 10.1016/j.vetmic.2009.09.054
10. Rossmanith W, Deinhofer M, Janacek R, Trampler R, Wilhelm E. Voluntary and compulsory eradication of bovine viral diarrhoea virus in Lower Austria. *Vet Microbiol.* (2010) 142:143–9. doi: 10.1016/j.vetmic.2009.09.055
11. Presi P, Struchen R, Knight-Jones T, Scholl S, Heim D. Bovine viral diarrhea (BVD) eradication in Switzerland-experiences of the first two years. *Prev Vet Med.* (2011) 99:112–21. doi: 10.1016/j.prevetmed.2011.01.012
12. Ståhl K, Alenius S. BVDV control and eradication in Europe–an update. *Jpn J Vet Res.* (2012) 60(Suppl):S31–9. doi: 10.14943/jjvr.60.suppl.s31
13. Loken T, Nyberg O. Eradication of BVDV in cattle: the Norwegian project. *Vet Rec.* (2013) 172:1–5. doi: 10.1136/vr.101525
14. Thomann B, Tschopp A, Magouras I, Meylan M, Schüpbach-Regula G, Häsler B. Economic evaluation of the eradication program for bovine viral diarrhea in the Swiss dairy sector. *Prev Vet Med.* (2017) 145:1–6. doi: 10.1016/j.prevetmed.2017.05.020
15. Santman-Berends IM, Mars MH, Van Duijn L, Van Schaik G. Evaluation of the epidemiological and economic consequences of control scenarios for bovine viral diarrhea virus in dairy herds. *J Dairy Sci.* (2015) 98:7699–716. doi: 10.3168/jds.2014-9255
16. Pinior B, Firth CL, Richter V, Lebl K, Trauffler M, Dzieciol M, et al. A systematic review of financial and economic assessments of bovine viral diarrhea virus (BVDV) prevention and mitigation activities worldwide. *Prev Vet Med.* (2017) 137(Part A):77–92. doi: 10.1016/j.prevetmed.2016.12.014
17. Moennig V, Becher P. Pestivirus control programs: how far have we come and where are we going? *Anim Health Res Rev.* (2015) 16:83–7. doi: 10.1017/S1466252315000092
18. Moennig V, Greiser-Wilke I. Perspectives on BVD eradication in Germany. *Berl Munch Tierarztl Wochenschr.* (2003) 116:222–6.
19. Greiser-Wilke I, Grummer B, Moennig V. Bovine viral diarrhoea eradication and control programmes in Europe. *Biologicals.* (2003) 31:113–8. doi: 10.1016/S1045-1056(03)00025-3
20. Schirrmeier H. Three years of mandatory BVD control in Germany–lessons to be learned. In: *Proceedings XXVIII World Buiatrics Congress*, Cairns, QLD (2014). p. 245.
21. Moennig V, Eicken K, Flebbe U, Frey HR, Grummer B, Haas L, et al. Implementation of two-step vaccination in the control of bovine viral diarrhoea (BVD). *Prev Vet Med.* (2005) 72:109–14. doi: 10.1016/j.prevetmed.2005.08.011
22. Anonymus. Verordnung zum Schutz der Rinder vor einer Infektion mit dem Bovinen Virusdiarrhoe-virus (BVDV-Verordnung) vom 11. Dezember 2008. *BGBl I.* (2008) 59:2461–66. Available online at: https://www.gesetze-im-internet.de/bvdvv/BJNR246110008.html
23. Wernike K, Gethmann J, Schirrmeier H, Schroder R, Conraths FJ, Beer M. Six years (2011-2016) of mandatory nationwide bovine viral diarrhea control in Germany-a success story. *Pathogens.* (2017) 6:50. doi: 10.3390/pathogens6040050
24. Kuhne S, Schroeder C, Holmquist G, Wolf G, Horner S, Brem G, et al. Detection of bovine viral diarrhoea virus infected cattle–testing tissue samples derived from ear tagging using an erns capture ELISA. *J Vet Med B Infect Dis Vet Public Health.* (2005) 52:272–7. doi: 10.1111/j.1439-0450.2005.00861.x
25. Wernike K, Schirrmeier H, Wolf G, Gethmann JM, Conraths FJ, Bätza HJ, et al. BVD-sanierung in Deutschland. *DTBl.* (2016) 6:829–34. Available online at: https://www.deutsches-tieraerzteblatt.de/fileadmin/resources/PDFs/Altdaten/DTBl_6_2016_BVDV_Entsperrt.pdf
26. Houe H. Bovine virus diarrhoea virus: detection of Danish dairy herds with persistently infected animals by means of a screening test of ten young stock. *Prev Vet Med.* (1994) 19:241–8. doi: 10.1016/0167-5877(94)90092-2
27. Houe H, Lindberg A, Moennig V. Test strategies in bovine viral diarrhea virus control and eradication campaigns in Europe. *J Vet Diagn Invest.* (2006) 18:427–36. doi: 10.1177/104063870601800501
28. Grimm V, Berger U, Bastiansen F, Eliassen S, Ginot V, Giske J, et al. A standard protocol for describing individual-based and agent-based models. *Ecol Model.* (2006) 198:115–26. doi: 10.1016/j.ecolmodel.2006.04.023
29. Bassett J, Blunk P, Isele T, Gethmann J, Hövel P. An agent-based model for bovine viral diarrhea. *arXiv [preprint]. arXiv:1812.06964.* (2018). Available online at: https://arxiv.org/abs/1812.06964
30. Bassett GJ. *Computational and Analytical Approaches Towards Epidemic Spread Containment of Temporal Animal Trade Networks*. Berlin: Technische Universität Berlin (2019).
31. R Core Team. *R: A Language and Environment for Statistical Computing.* Vienna: R Foundation for Statistical Computing (2018).
32. Viet A-F, Fourichon C, Seegers H, Jacob C, Guihenneuc-Jouyaux C. A model of the spread of the bovine viral-diarrhoea virus within a dairy herd. *Prev Vet Med.* (2004) 63:211–36. doi: 10.1016/j.prevetmed.2004.01.015
33. Graham DA, Clegg TA, O'sullivan P, More SJ. Survival time of calves with positive BVD virus results born during the voluntary phase of the Irish eradication programme. *Prev Vet Med.* (2015) 119:123–3. doi: 10.1016/j.prevetmed.2015.02.011
34. Anonymus. *Zweite Verordnung zur Änderung der BVDV-Verordnung*. (2016). Drucksache 200/16 vom 20.04.16. Available online at: https://www.bundesrat.de/SharedDocs/drucksachen/2016/0101-0200/200-16.pdf
35. Rushton J, Thornton PK, Otte MJ. Methods of economic impact assessment. *Rev Sci Tech OIE.* (1999) 18:315–42. doi: 10.20506/rst.18.2.1172
36. Häsler B, Howe KS, Presi P, Stärk KDC. An economic model to evaluate the mitigation programme for bovine viral diarrhoea in Switzerland. *Prev Vet Med.* (2012) 106:162–73. doi: 10.1016/j.prevetmed.2012.01.022
37. Valle PS, Skjerve E, Martin SW, Larssen RB, Osteras O, Nyberg O. Ten years of bovine virus diarrhoea virus (BVDV) control in Norway: a cost-benefit analysis. *Prev Vet Med.* (2005) 72:189–207. doi: 10.1016/j.prevetmed.2005.07.017

38. Stott AW, Humphry RW, Gunn GJ, Higgins I, Hennessy T, O'flaherty J, et al. Predicted costs and benefits of eradicating BVDV from Ireland. *Irish Vet J*. (2012) 65:12. doi: 10.1186/2046-0481-65-12
39. Scharnböck B, Roch F-F, Richter V, Funke C, Firth CL, Obritzhauser W, et al. A meta-analysis of bovine viral diarrhoea virus (BVDV) prevalences in the global cattle population. *Sci Rep*. (2018) 8:14420. doi: 10.1038/s41598-018-32831-2
40. Santman-Berends IMGA, Mars MH, Van Duijn L, Van Den Broek KWH, Van Schaik G. A quantitative risk-analysis for introduction of Bovine Viral Diarrhoea Virus in the Netherlands through cattle imports. *Prev Vet Med*. (2017) 146:103–13. doi: 10.1016/j.prevetmed.2017.08.003
41. Marschik T, Obritzhauser W, Wagner P, Richter V, Mayerhofer M, Egger-Danner C, et al. A cost-benefit analysis and the potential trade effects of the bovine viral diarrhoea eradication programme in Styria, Austria. *Vet J*. (2018) 231:19–29. doi: 10.1016/j.tvjl.2017.11.010
42. Frey HR, Flebbe U, Liess B. Prävalenz und klinische Symptomatik persistenter BVD-Virusinfektionen in Rinderbeständen Niedersachsens. *Prakt Tierarzt*. (1996) 1:49–52.
43. Bachofen C, Stalder H, Vogt HR, Wegmuller M, Schweizer M, Zanoni R, et al. Bovine viral diarrhea (BVD): from biology to control. *Berl Munch Tierarztl Wochenschr*. (2013) 126:452–61. doi: 10.2376/0005-9366-126-452
44. Bendfeldt S, Grummer B, Haas L, Staubach C, Moennig V, Liess B. Seroprevalences in four different counties in Lower Saxony and the relevance for the control strategie. *Tierarztl Umschau*. (2004) 59:499–507.
45. Rufenacht J, Schaller P, Audige L, Strasser M, Peterhans E. Prevalence of cattle infected with bovine viral diarrhoea virus in Switzerland. *Vet Rec*. (2000) 147:413–7. doi: 10.1136/vr.147.15.413
46. Schreiber P, Dubois F, Dreze F, Lacroix N, Limbourg B, Coppe P. Prevalence of bovine virus diarrhoea virus infection in Belgian white blue cattle in southern Belgium. *Vet Quart*. (1999) 21:28–32. doi: 10.1080/01652176.1999.9694987
47. Sarrazin S, Veldhuis A, Meroc E, Vangeel I, Laureyns J, Dewulf J, et al. Serological and virological BVDV prevalence and risk factor analysis for herds to be BVDV seropositive in Belgian cattle herds. *Prev Vet Med*. (2013) 108:28–37. doi: 10.1016/j.prevetmed.2012.07.005
48. Tinsley M, Lewis FI, Brulisauer F. Network modeling of BVD transmission. *Vet Res*. (2012) 43:11. doi: 10.1186/1297-9716-43-11
49. Thulke HH, Lange M, Tratalos JA, Clegg TA, Mcgrath G, O'grady L, et al. Eradicating BVD, reviewing Irish programme data and model predictions to support prospective decision making. *Prev Vet Med*. (2018) 150:151–61. doi: 10.1016/j.prevetmed.2017.11.017
50. Iotti B, Valdano E, Savini L, Candeloro L, Giovannini A, Rosati S, et al. Farm productive contexts and the dynamics of bovine viral diarrhea (BVD) transmission. *Prev Vet Med*. (2019) 165:23–33. doi: 10.1016/j.prevetmed.2019.02.001
51. Fourichon C, Beaudeau F, Bareille N, Seegers H. Quantification of economic losses consecutive to infection of a dairy herd with bovine viral diarrhoea virus. *Prev Vet Med*. (2005) 72:177–81. doi: 10.1016/j.prevetmed.2005.08.018
52. Wolf G. (2003). Available online at: https://www.kreis-as.de/Unser-Landkreis/Gesundheit-Verbraucherschutz/Veterin%C3%A4ramt/Tierseuchen/BVD-MD/Schadenskalkulation (assessed December 14, 2018).
53. Hogeveen H, Meuwissen MPM, Huirne RBM. *Verzekeren van Diergezondheid in de Melkveesector: een Risico-Analyse*. Wageningen: S.n. (2003).

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

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Animal Hygiene Indexes in Relation to Big-Five Personality Traits of German Pig Farmers Evaluated by Self- and Other-Rating

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Improving biosecurity in intensive livestock production has become an increasingly challenging task. Often, animal hygiene measures are implemented at lower levels than recommended. Therefore, veterinarians and farm advisors look for new approaches to improve their advisory process with farmers. In the current study it has been hypothesized that German pig farmers' big-five measured personality traits might correlate with farms' biosecurity level expressed by a "continuous animal hygiene index" and a "technical animal hygiene index." Hence, comprehensive data on the implementation of more than 100 hygiene measures were collected at farm level from a specific pilot sample of 42 pig farmers from a livestock intensive region in north-western Germany. In addition, big-five personality traits (BFI-S) were measured by self- and other-rating. Inter-rater reliabilities for personality traits indicated expected positive correlations apart from agreeableness ($r_S = -0.101$). Regarding the self-rating, neuroticism was valued lowest ($\bar{x} = 3.88 \pm 1.18$) and conscientiousness highest ($\bar{x} = 5.68 \pm 0.70$). The animal hygiene indexes revealed medium biosecurity levels on the participating farms. Piglet breeders had a significantly higher value for the "continuous animal hygiene index" ($\bar{x} = 63.00 \pm 9.91\%$). Personality traits conscientiousness and openness showed correlations with the continuous and the technical animal hygiene index. Depending on the production systems as well as the rating perspectives, correlations varied. For one of the personality traits playing a direct role in social interaction—extraversion—the advisory process might function as a mediating factor. The current results show that clustering of single hygiene measures into indexes in the evaluation of pig farms' biosecurity level might have advantages. The preliminary results from this study should be validated in larger, more representative samples. Furthermore, structured and systematic consideration of personality traits of farmers adds an additional aspect to include individuality of farmers more systematically in complex advisory processes. Interaction of personality traits with characteristics of the advisory process should be further researched and should be included in a much broader socio-political understanding of what is involved in changing practices.

Keywords: pig farmer, biosecurity, animal hygiene, personality, advisory process

INTRODUCTION

Animal hygiene has become a "mainstream prerequisite for an ethically accepted and sustainable production of food from animals" (1). Nevertheless, measures to enhance animal hygiene are often implemented at levels lower than recommended. Not least of all, animal performance could increase, if animal health and hygiene were enhanced (2). Therefore, there has been a recent increase in research aimed at a valid evaluation of current biosecurity levels and practicing biosecurity measures on livestock farms [e.g., (3–6)]. But even when biosecurity levels were regularly highlighted as strongly in need of improvement, reasons for low implementation were often unclear.

Zoonotic diseases, which can affect food animal populations as well as human health, still play a major role (7). Especially intensive pig livestock regions, such as the north-western part of Germany, are susceptible to epidemic outbreaks. Concerning the African swine fever, for example, there is a high risk of dissemination from Eastern Europe through food leftovers, feral pigs as well as pig livestock imported to Germany. Dissemination depends on biosecurity levels of pig farms (8), among others. Whereas, the African swine fever does not harm humans, pig-transmitted Methicillin-resistant Staphylococcus aureus (MRSA) colonization of German farm workers has been proven in several studies [e.g., (9, 10)]. So, the level of endemic infection of pig herds is relevant concerning hospital-transmitted MRSA infections (11). Further examples given are Salmonella infections, whose harm is not limited to pig health. Nowadays, people still become ill by food-borne salmonellosis infections (12–14). They also cause the most deaths regarding foods of animal origin in Germany (15). Therefore, the implementation of biosecurity measures on livestock farms as a preventive approach has become an increasingly important task.

Here the question arises of how implementation of measures can be enhanced at the farm level. Implementation deficits have been identified in several studies [e.g., (5, 16, 17)]. Research clearly showed that pure knowledge about useful on-farm measures with concern to livestock husbandry is lost before their implementation (18, 19). It was also shown that biosecurity measures were considered derogatorily by many farmers (20). Distinctly, perceptions and attitudes toward the implementation of single hygienic measures at any rate, recommended by science and mediated by veterinarians or farm advisors, have been a worldwide problem for years, as discussed by Racicot et al. (4). Hence, veterinarians and farm advisors look for new approaches to overcome the lack of implementation of measures. Moreover, these persons are the most important ones, who can highly impact on farmers' decision making and attitudinal behavior (16, 21–26). Therefore, communication and understanding between all agents is necessary (16).

Veterinarians and farm advisors need science's support to get access to valid and feasible tools, being applicable during farm visits. Indeed, veterinary epidemiology in combination with social sciences maintains a multidisciplinary approach. It is difficult to let results intertwine (24). Obstacles were attributed to researchers' specializations. Relevant interdisciplinary cooperation between veterinary and social sciences is often still missing. Following this scientific background, the most important and difficult tasks are still prospectively, (1) to be able to define the origin of farmers' general understanding and decision making behavior with regards to farm operating strategies and (2) to meet the challenge of deriving action strategies for veterinarian personnel and farm advisors.

In recent years there have been different approaches to analyze, especially psychological, motivational as well as social factors explaining and predicting farmers' behavior in relation to veterinary epidemiology as well as infectious diseases among farm animals (19, 21, 23, 27). Additionally, increasing research is available in which farmers' personality traits were assessed in relation to non-epidemic as well as health topics. Reliable predictors of their behavior could be identified (28–30). Thereby, the five-factor personality model or rather the big-five model, as a method originated in the "psycho-lexical-tradition" (31, 32) in combination with the "differentiated and clinical tradition of the personality research" (33, 34) was implemented successfully several times on different farmers [e.g., (35)]. Regarding farms' disease control as well as farms' biosecurity compliance, researchers found that several personality traits are highly correlated for the assessed dependent variables and measures (4, 36, 37). Because of these recently obtained and demonstrably useful signs on the applicability of the big-five personality model on cattle as well as poultry farmers, this model was chosen in the current study with intensive pig farms. Here, it has been generally hypothesized that farmers' big-five measured personality traits might have significant impact on pig farms' biosecurity levels. Hypothetically, information on farmers' personalities could support veterinarians and farm advisors to develop more tailored advisory processes and strategies.

Therefore, the first aim of the current study was to test the big-five model "BFI-S" (38) for reliability by self- and other-rating, which has not been done in animal health-related studies before. The sample comprised 42 German intensive pig livestock farmers. They were part of a more comprehensive three-year research project. The second aim was appraising the implementation level of biosecurity measures. For this purpose, a survey of farmers participating in the project was conducted by two researchers during a farm visit. The third aim of the present study was to analyze the impact of big-five measured personality traits on the farms' biosecurity levels. Therefore, it was hypothesized that different measures occurring on farms were influenced, to various extents, by different personality traits (**Figure 1**).

DATA AND METHODS

Project Design

Farmers participating in the current study joined the three-year project "Preventive hygienic consulting" which ran from 2014 to 2017. The project was for improving animal hygiene in intensive, conventional pig production in a livestock-intensive region in the state of North Rhine-Westphalia in north-western Germany. The project included workshops on biosecurity measures, possibility for on-farm research trials, farm individual biosecurity

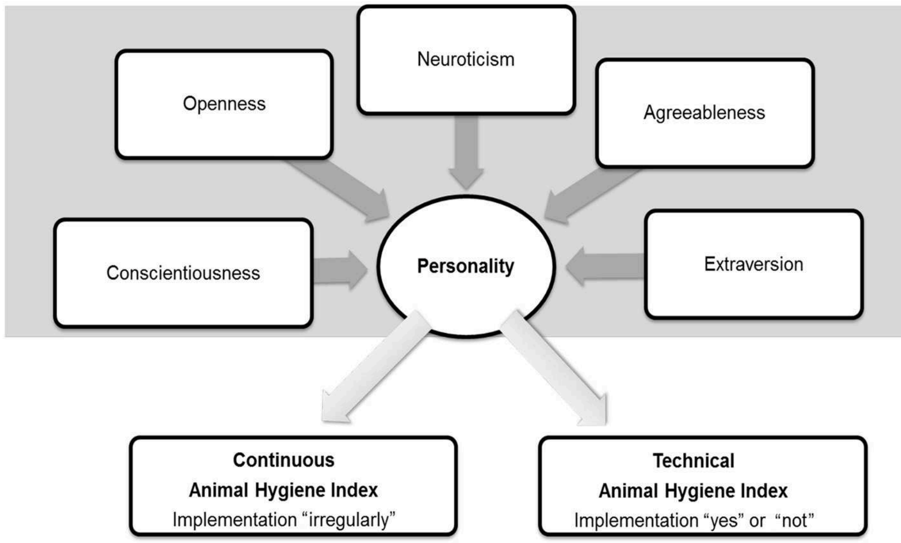

FIGURE 1 | Big-five model with the five personality traits aligning the "continuous animal hygiene index" and the "technical animal hygiene index" with their frequencies of implementation of measures.

consulting and the possibility to engage a professional pest-control operator at subsidized fees. Farmers were suggested by regional advisors from different organizations and veterinarians to participate in two project information workshops in October 2013. Due to the pilot character of the present study, it was seen as essential to work within established on-farm research structures and build on trust relationships with these farmers. All farmers were pig producers at different levels in the production chain. Famers in our sample were from three production systems of "breeding sow keepers" ($N = 8$), "piglet breeders" ($N = 10$), and "fattening pig keepers" ($N = 24$). The three different production systems chosen were classified according to common conditions as follows:

1. BSK: Breeding sow keepers (sows and piglets till 8 kg body weight)
2. PB: Piglet breeders (piglets from 8 to 25 kg body weight)
3. FPK: Fattening pig keepers (pigs from 25 kg body weight to slaughter weight)

As shown in **Table 1**, some farms were comprised of two or all three production systems with every possible combination. Thus, for the current analyses, farms were classified according to the production system self-selected by farmers. Data were based on stables and partly accounted for overall farm hygiene. On average, breeding sow keepers kept 438 ± 125 sows, piglet breeders 1,265 ± 673 piglets and fattening pig keepers 2,262 ± 1,434 pigs.

Participation in the research project was voluntary. Project data for this study was collected by the help of two questionnaires within face-to-face interviews. The first was the "intensive farm questionnaire," which was implemented to build animal hygiene indexes. Furthermore, overall project evaluation data as well as big-five personality traits assessed by self- and other-rating were collected by the "concluding farm questionnaire." Data was collected in such a way that data from the two different surveys could be linked for each farm.

TABLE 1 | Number of kept animals disaggregated by production systems.

	Sows	Piglets	Fattening pigs
	$\bar{x} \pm \bar{x}$	$\bar{x} \pm \bar{x}$	$\bar{x} \pm \bar{x}$
Breeding sow keepers (BSK)	438 ± 125 (8*)	1,253 ± 799 (6)	640 ± 792 (2)
Piglet breeders (PK)	360 ± 310 (5)	1,265 ± 673 (10)	1,288 ± 165 (4)
Fattening pig keepers (FPK)	84 (1)	643 ± 367 (3)	2,262 ± 1,434 (24)

Number of farms in brackets.

Intensive Farm Questionnaire

A comprehensive questionnaire was developed and implemented on farms from January to April 2014 in order to conduct a detailed overall evaluation of the hygienic situations. The survey was done face-to-face with the respective farmers by two researchers during a farm visit. A specific questionnaire was developed for each different production system containing specific items referring to the production system in question, as well as containing an equal main part, which was divided into six farm compartments (**Table 2**). Biological performance indicators were queried as well but not included in the current study. Most of the items were polar questions with predefined reply classes. Depending on the type of question, each reply class was named or only the polar points were named. Additionally, some open questions were asked and constitute additional items.

Animal Hygiene Index

As measures are implemented on farms to varying degrees, the items of the "intensive farm questionnaire" were firstly divided by their frequency of measure implementation. Following this, there were two kinds of frequencies. The first concerns whether or not measures are continuously implemented or, if they are generally conducted or not. The latter were related to structural conditions and considered as technical measures. Thus, a detailed definition of the "continuous animal hygiene index" and the technical hygiene index is presented in the following two sections.

TABLE 2 | Farm compartments comprised by the "intensive farm questionnaire" for the production systems breeding sow keepers, piglet breeders, and fattening pig keepers.

Farm compartment	
1	Stable
2	Farm organization
3	Farm hygiene
4	Stable climate
5	Health prophylaxis
6	Biological performances

Continuous Animal Hygiene Index (CAHI)

The "continuous animal hygiene index" includes operational measures conducted at different frequencies, even if they should be carried out regularly. Regularly means in relation to the intended objective (once or more times a day, once after emptying the stable, etcetera). These measures relate to the farmers' operational behavior and decisions. Examples of measures considered in this index are listed in **Table 3**.

Technical Animal Hygiene Index (TAHI)

The "technical animal hygiene index" relates to measures of structural implementation and in relation to technical conditions. As such, these measures relate to farmers' strategic behavior and decision-making. Examples of measures considered in this index are provided in **Table 4**.

TABLE 3 | Number of items according to the production systems and content examples of items related to the "continuous animal hygiene index" (CAHI).

Production system	Number of items	Content of items				
Breeding sow keepers (BSK) ($N = 8$)	80	Take on/off farm-owned protection clothes	Cleaning/disinfecting protecting shoes	Cleaning appliances/water/ feed pipelines	Conducting deworming	Dissection of pigs with unknown cause of death
Piglet breeders (PB) ($N = 10$)	67					
Fattening pig keepers (FPK) ($N = 24$)	72					
		Answer options				
		Always/ mostly/ sometimes/ never	Always/ mostly/ sometimes/ never	After every trial/ yearly/ sometimes/ never	Yes/ partly/ no	Always/ partly/ rarely/ never

TABLE 4 | Number of items according to the production systems and content examples of items related to the "technical animal hygiene index" (TAHI).

Production system	Number of items	Content of items				
Breeding sow keepers (BSK) ($N = 8$)	38	General structural state of the stable	Conducting the "all in - all out" and "black—white' system	Providing a changing room with shower and visitor protocol	Storage of feed and litter saved from sun and animals	Conduction of water samples analyses and water disinfection
Piglet breeders (PB) ($N = 10$)	34					
Fattening pig keepers (FPK) ($N = 24$)	38					
		Answer options				
		Very good/ good/ in need of renovation/ very in need of renovation	Yes/ no	Yes/ no	Yes/ partly/ no	Yearly/ if required/ never

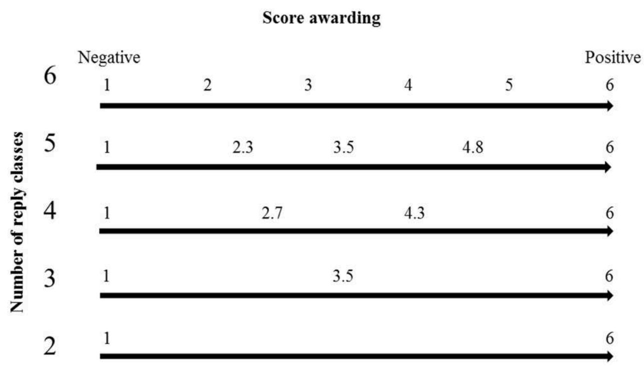

FIGURE 2 | Score awarding for the animal hygiene indexes (CAHI, TAHI) for two to six reply classes.

Animal Hygiene Index Calculation

The animal hygiene indexes (CAHI and TAHI) were calculated as two separate indexes for every single farm. Thereby, all items were assigned either to be included in the CAHI or in the TAHI calculation. Secondly, the points given for every question were divided proportionally to the number of reply classes as shown in **Figure 2**. High levels of implementation correspond to six points and low levels to one point. The numbers of reply classes reflect the implementation of measures (i.e., the frequency of implementation of measures or if specific structural conditions are present or not). If no hygiene measures were implemented, this was evaluated by one point. Further open answers were coded to reply classes, too. These reply classes were defined ex-post to the survey during data analysis. Examples include the type of washing equipment for shoes or the strategy to reduce flies. Afterwards, all items were weighted based on their relevance with regard to hygiene levels by factor multiplication. The factors run from 1 (low factor loading) over 2 (medium factor loading) to 3 (high factor loading). The ranking was carried out by the three researchers conducting this study, all having a pig production advisory background. Altogether, the CAHI and the TAHI each represent the sum of the achieved question points multiplied with the determined factors for every single farm, always in relation to the maximal reachable sum of points over all items, as the following formula shows.

$$V_{\frac{C}{T}}\left(j\right) = 1/z \sum_{i=1}^{q} (x_{ij} * y_i) * 100\% \qquad (1)$$

V_C = Value of "continuous animal hygiene index" (CAHI)
V_T = Value of "technical animal hygiene index" (TAHI)
i = Items
j = Farmer
q = Number of items
x = Scored number of reply classes
y = Factor-loading
z = Maximal reachable sum of points from all items.

Concluding Farm Questionnaire

The "concluding farm questionnaire" was designed for a final project evaluation. Therefore, farmers were visited again during December 2016 to February 2017. This questionnaire evaluated the overall project at the end, i.e., if the project measures provided resulted in increased hygienic conditions on farms; if the farmers' hygienic awareness has changed. Both aims were not the focus of the current study. Parts of the project evaluation results have been published by Wildraut et al. (39) and Hecker et al. (40). The big-five assessment was included in the "concluding farm questionnaire" as explained in the following section.

Big-Five Personality (BFI-S) Assessment

For the personality trait assessment, the "BFI-S" from Schupp and Gerlitz (38) was chosen. The farmers valued their approval or disapproval for the items (for items' content, see the second column of **Table 5**; items were linguistically shortened) on terminal seven-pointed Likert scales ("does not apply at all" to "fully applies"). For the self-ratings, all items started with "I am somebody, who...." For the other-rating, the items started with "The farmer is somebody, who. . . ." For the other-rating, the person was an affiliated person who knew the farmer well. As the study was done in a context with family farms, the farmers' wives were mostly chosen by the farmers as the person doing the other-rating. Reverse scaled items were rescaled before data analysis was conducted, so that all items were expressed positively: High scale values mean high approval (see column "item-polarity" in **Table 5**). Results were always presented for the self- and other-rating.

Statistical Analyses

Data entry was done with Microsoft Excel 2010 and statistical analyses with IBM SPSS Statistics 25. All data were first analyzed descriptively. Afterwards, data were tested for homogeneity of variances and normal distribution using the Levene and Kolmogorov-Smirnov procedures, respectively. Variance homogeneity was given for all BFI-S personality traits except neuroticism. Additionally, sample sizes for the farmers of the three different production systems differed widely. Hence, differences between personality traits and production systems were analyzed by the Hochberg GT2 procedure ($\alpha = 0.05$) after using the univariate ANOVA.

Differences of the big-five traits (dependent variable) between production system (independent variable) were analyzed answering the question if personalities of farmers differ between production systems.

Concerning the continuous (CAHI) and technical animal hygiene indexes (TAHI), variances were homogenous and data were distributed normally for the technical index (TAHI). Regarding the different sample size of the production systems and the robustness of the Hochberg GT2 procedure ($\alpha = 0.05$) against non-normal distributed data, this test was chosen for analyzing the differences of the indexes (dependent variable) between pig production systems (independent variable), answering the question if implementation of hygiene measures differs between production systems.

TABLE 5 | Means, standard deviation, medians, inter-rater-, and inter-item correlations (r_S, $^*p \leq 0.05$, $^{**}p \leq 0.01$) of the big-five traits based on the BFI-S for intensive pig keepers ($N = 42$).

Trait	Item	Item-no. (Item-polarity)	Means ± standard deviation (Median)		Differences of the means	Inter-item correlations			Interrater-correlation
			Self	Other		Items	Self	Other	
Extraversion	communicative, talkative	1 (+)	5.38 ± 0.96 (6.0)	5.95 ± 1.08 (6.0)	−0.57 ± 1.15	1↔2	0.443**	0.205	0.397**
	reserved	2 (–)	3.36 ± 1.41 (4.0)	4.45 ± 1.85 (4.0)	−0.10 ± 2.02	2↔3	0.411**	0.452**	0.268
	outgoing, sociably	3 (+)	5.17 ± 1.17 (5.0)	5.95 ± 1.13 (6.0)	−0.79 ± 1.14	1↔3	0.452**	0.442**	0.530**
	Mean		**4.97 ± 0.93 (5,0)**	**5.45 ± 1.01 (5.3)**	**−0.48 ± 0.92**				**0.515****
Conscientiousness	working thoroughly	1 (+)	5.57 ± 0.86 (6.0)	6.24 ± 0.93 (6.0)	−0.67 ± 0.93	1↔2	0.520**	0.675**	0.393**
	effective and efficient	2 (+)	5.81 ± 0.80 (6.0)	6.14 ± 1.20 (6.5)	−0.33 ± 1.20	2↔3	0.073	0.260	0.351*
	rather lazy	3 (–)	5.67 ± 1.39 (6.0)	6.43 ± 1.42 (7.0)	−0.76 ± 1.59	1↔3	0.225	0.374*	0.139
	Mean		**5.68 ± 0.70 (5,7)**	**6.27 ± 0.93 (6.5)**	**−0.59 ± 0.95**				**0.212**
Neuroticism	getting nervous easily	1 (+)	3.69 ± 1.62 (4.0)	3.52 ± 1.80 (3.0)	0.17 ± 1.67	1↔2	0.325*	0.644**	0.518**
	relaxed, doing well with stress	2 (–)	3.55 ± 1.44 (3.5)	3.29 ± 1.73 (3.0)	0.26 ± 2.10	2↔3	0.112	0.019	0.179
	worrying often	3 (+)	4.40 ± 1.77 (4.5)	4.43 ± 1.71 (4.5)	−0.02 ± 1.92	1↔3	0.477**	0.194	0.326*
	Mean		**3.88 ± 1.18 (3,8)**	**3.75 ± 1.27 (3.7)**	**0.14 ± 1.21**				**0.440****
Openness	appreciating artistic experiences	1 (+)	3.40 ± 1.56 (4.0)	3.88 ± 1.66 (4.0)	−0.48 ± 1.74	1↔2	−0.160	0.246	0.420**
	vivid phantasy, having imagination	2 (+)	4.57 ± 1.42 (5.0)	4.38 ± 1.55 (4.0)	0.19 ± 1.86	2↔3	0.153	0.602**	0.170
	ingenious, introducing new ideas	3 (+)	5.02 ± 1.32 (5.0)	5.60 ± 1.08 (6.0)	−0.57 ± 1.58	1↔3	−0.032	0.331*	−0.066
	Mean		**4,33 ± 0,76 (4,3)**	**4.62 ± 1.10 (4.7)**	**−0.29 ± 1.17**				**0.216**
Agreeableness	considering and friendly	1 (+)	5.71 ± 0.86 (6.0)	5.86 ± 1.07 (6.0)	−0.14 ± 1.56	1↔2	0.362*	0.551**	−0.275
	sometimes rude to others	2 (–)	5.17 ± 1.40 (5.0)	5.55 ± 1.58 (6.0)	−0.38 ± 2.06	2↔3	0.180	0.317*	0.113
	forgiving	3 (+)	5.57 ± 1.09 (6.0)	5.74 ± 1.38 (6.0)	−0.17 ± 1.78	1↔3	0.124	0.280	0.178
	Mean		**5,48 ± 0,76 (5,7)**	**5.71 ± 1.02 (5.8)**	**−0.23 ± 1.39**				**−0.101**

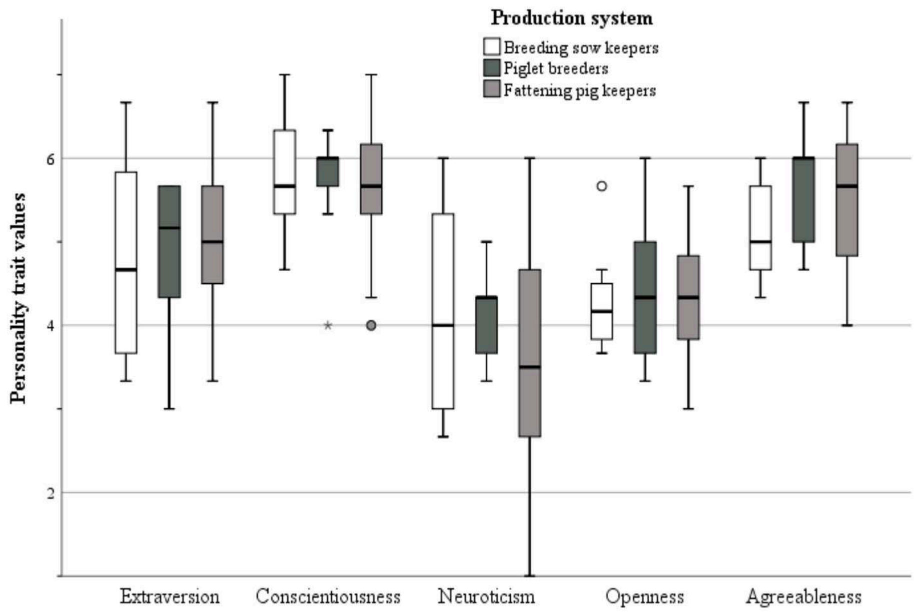

FIGURE 3 | Box-and-whisker plot of personality trait values according to the pig production system: breeding sow keeper ($N = 8$), piglet breeders ($N = 10$) and fattening pig keepers ($N = 24$).

Inter-rater and inter-item correlations of the big-five personality traits were calculated. Inter-rater correlation refers to the correlation between self- and other-rating. High correlations indicate a high reliability of the measured item. Inter-item correlations refer to correlations between the three single items of each personality trait. High correlations indicate high internal construct validity of the respective personality traits. Since items were measured as ordinate variables, the Spearman rank-correlation (r_S) was used. Together, these analyses were implemented to test for the consistency of the big-five personality model in the context of this study. For comparison of the continuous (CAHI) and "technical animal hygiene index" (TAHI) as metric parameters, the Pearson correlation was calculated (r_P). Correlations of the big-five personality traits by self- and other-rating with the "continuous animal hygiene index" (CAHI) and the "technical animal hygiene index" (TAHI) were analyzed by the Spearman rank-correlation (r_S). These analyses answer the key question of the study whether personality traits are correlated with the implementation level of hygiene measures. The reference unit for all analyses was the farms (always $N = 42$).

RESULTS

Inter-rater and Inter-item Correlations

Regarding the self-ratings with an average value of 5.68 ± 0.11 for conscientiousness, this trait was valued highest, followed by agreeableness ($\bar{x} = 5.48 \pm 0.12$, **Table 5**) and extraversion ($\bar{x} = 4.79 \pm 0.14$). Openness was valued with 4.33 ± 0.12 on average and neuroticism lowest ($\bar{x} = 3.88 \pm 0.18$). The highest mean difference between self- and other-rating was 0.59 ± 0.95 data points, which was related to conscientiousness. The other-rating always resulted in higher valued items.

Regarding the self-rating, inter-item correlations were significant concerning extraversion as well as particularly concerning conscientiousness, neuroticism as well as agreeableness. Regarding other-rating, correlation was found between two pairs of items in relation to extraversion, conscientiousness, openness, and agreeableness, whilst only one pair of items was significant for neuroticism. Significant inter-rater correlations were found for some of the personality traits (**Table 5**).

Differences Between the Production Systems for the BFI-S Traits

Differences between all five of the personality traits were not significant in relation to the three production systems "breeding sow keepers" (BSK), "piglet breeders" (PB), and "fattening pig keepers" (FPK) (extraversion: $F = 0.267$, $p = 0.767$; conscientiousness: $F = 0.140$, $p = 0.870$; neuroticism: $F = 0.702$, $p = 0.502$; openness: $F = 0.110$, $p = 0.896$; agreeableness: $F = 1.355$, $p = 0.270$). As a tendency, piglet breeders valued themselves highest in all traits (**Figure 3**). In this production type, conscientiousness as well as agreeableness was valued highest with always a median of six. Lowest values were chosen for openness ($\tilde{x} = 4$) and neuroticism ($\tilde{x} = 4$). Breeding sow keepers valued themselves highest in regards to conscientiousness ($\tilde{x} = 6$) and lowest regarding neuroticism ($\tilde{x} = 4$) and openness ($\tilde{x} = 4$), when comparing the different traits within this production system. Further, the fattening pig breeders had the widest standard deviation for neuroticism with additionally the lowest

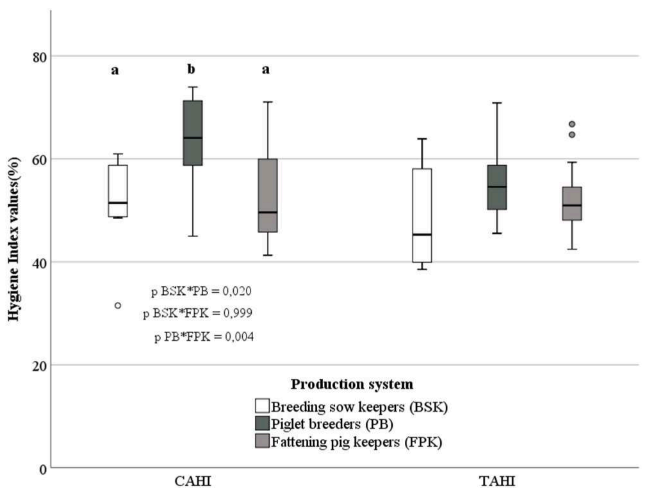

FIGURE 4 | Box-and-whisker plot of continuous and "technical animal hygiene index" values (%) according to the pig production systems. Different letters indicate significant differences (ANOVA and Hochberg GT2 procedure; α = 0.05); *p*-values of pairwise comparisons are given below the box-and-whisker plots.

TABLE 6 | Spearman correlations (r_S, $p^* \leq 0.05$) of the big-five personality traits (BFI-S) by self- and other-rating with the "continuous animal hygiene index" and the "technical animal hygiene index" according to the production systems.

Trait	Continuous animal hygiene index					
	Self-rating			Other-rating		
	BSK	PB	FPK	BSK	PB	FPK
Extraversion	−0.455	0.624	0.251	0.072	0.265	−0.132
Conscientiousness	−0.265	0.519	0.453*	0.049	0.304	−0.010
Neuroticism	0.386	0.120	−0.094	0.570	−0.161	−0.248
Openness	0.497	0.530	0.140	0.220	0.332	−0.183
Agreeableness	0.170	0.000	−0.236	0.563	−0.086	0.202
	Technical animal hygiene index					
Extraversion	−0.467	−0.333	0.097	−0.012	−0.691*	−0.177
Conscientiousness	−0.072	0.337	0.419*	−0.195	0.076	0.126
Neuroticism	0.169	−0.031	−0.060	0.218	0.019	0.118
Openness	0.764*	−0.439	0.389	0.293	−0.049	−0.188
Agreeableness	0.485	0.058	−0.022	0.240	0.295	−0.070

BSK, Breeding sow keepers (N = 8); PB, Piglet breeders (N = 10); FPK, Fattening pig keepers (N = 24); All, All farmers (N = 42).

median value ($\tilde{x} = 4$). They rated themselves highest with conscientiousness and agreeableness (always $\tilde{x} = 6$).

Differences Between the Production Systems for the CAHI and TAHI

The value for the CAHI was significantly higher for piglet breeders in comparison with breeding sow keepers and fattening pig keepers (**Figure 4**). Breeding sow keepers and fattening pig keepers did not differ significantly ($p = 0.999$) with regard to the CAHI. Regarding the TAHI, no significant differences occurred between the three systems ($F = 1.837$, $p = 0.173$). The Pearson correlation between the indexes revealed a significant positive but medium result concerning fattening pig keepers ($r_P = 0.639$, $p = 0.01$). Further medium non-significant correlation occurred for breeding sow keepers ($r_P = 0.607$) and low negative correlation for piglet breeders ($r_P = -0.188$), which was not significant either. Altogether, the indexes correlated significantly but with moderate value ($r_P = 0.451$, $p = 0.01$).

Big-Five Personality Traits in Correlation With the CAHI and TAHI

Few significant correlations were found between the hygiene indexes and personality traits (**Table 6**). For example, significant correlations occurred with the fattening pig breeders (FPB), who achieved higher index values for both indexes, when conscientiousness was valued higher regarding the self-rating (CAHI: $r_S = 0.453$, $p = 0.05$; TAHI: $r_S = 0.419$, $p = 0.05$). With regards to breeding sow keepers (BSK), openness is significantly and highly positively correlated with the TAHI in respect to the self-rating ($r_S = 0.764$, $p = 0.05$). For the piglet breeders' (PB) other-rating, there is a significant negative correlation for extraversion with the TAHI ($r_S = -0.691$, $p = 0.05$).

DISCUSSION

Inter-rater and Inter-item Correlations of Big-Five Personality Items and Traits

Inter-rater reliabilities as well as inter-item reliabilities indicated mostly expected signs of the correlation coefficients. Inter-item correlations were predominantly in medium range with partially significant results. In general, lower correlations occurred within self-ratings. The results give first indications about the appropriateness of single items for evaluating personality traits when using the BFI-S among pig farmers. In addition, for single items as well as personality traits wide standard deviations were observed, especially for other-ratings. This is an indication that farmers' personality differences can be evaluated with the BFI-S and there are no stereotypical valuations.

Certain problems can be detected to measure the trait openness. For "appreciating artistic experiences" as well as "ingenious, introducing new ideas" from the openness trait, low negative correlations were found ($r_S = -0.160$ and -0.032) in the self-ratings. With the item "appreciating artistic experiences," Lang et al. (41) also identified inconsistent correlations in the self-ratings while testing for item-reliability. Perhaps this trait should be rephrased or even exchanged by another item in future self-ratings. Openness should possibly be rather assessed by other-ratings as inter-item correlations where considerably higher for other-ratings. Additionally, with conscientiousness as well as agreeableness, higher inter-item correlations regarding the other-rating could be identified.

The low negative yet non-significant total inter-rater correlations for agreeableness were caused by low inter-rater correlations for single items. In particular, the item "considering and friendly with others" did not correlate between self- and other-rating. Similar findings on agreeableness were found by Conelly and Ones (42), who did a meta-analytical study on observers' accuracy. This study found that for traits which were high in being evaluative—as agreeableness—personal closeness does not lead to higher inter-rater reliability. With agreeableness, inter-item correlations were higher for other-ratings than for self-ratings. This gives an indication that agreeableness should rather be measured by other-ratings in future studies.

Total inter-rater correlations appeared significant for extraversion and neuroticism. However, Vazire (43) found that neuroticism is assessed more reliably by other-rating. Indeed, this was not found in the present study. Here inter-item-reliability was good for self- and other-rating, and inter-rater reliability was good ($r_S = 0.440$, $p = 0.01$). A review on work performance and personality discovered that neuroticism's prediction ability was not at all satisfying (44). The authors concluded that broader constructed items would make this trait more valid. With "resiliency" vs. "internalizing negative emotionality" as opposed to neuroticism, the "Questionnaire Big Six Scale" could meet these requirements with greater validity.

Due to medium satisfaction with the reliability of the BFI-S, the implementation of a more specialized personality trait questionnaire, such as the "Questionnaire Big Six Scale," could lead to more reliable results. In that model, "honesty-humility" is separated from agreeableness into an independent sixth personality trait. Additionally, different subsets of the original 120-item survey (45) are available and already tested for item validity (46, 47). For practical reasons, it might be difficult to use longer survey tools.

Overall, the results of the present study give a first indication that the BFI-S model could be a valid tool to measure pig farmers' personality traits. Yet, as the focus of this study has been much broader than testing the validity of the BFI-S model and as the sample size has been limited, more specific studies are required for validation of the BFI-S among pig farmers. Special focus should be given on self- and other-ratings as the present study gives indication that they differ in their reliability depending on the type of personality trait to be evaluated. Openness and agreeableness especially might be evaluated more consistently by other-ratings. This would be a challenge for many empirical studies as data on self-ratings can be collected much easier than data on other-ratings.

The CAHI and the TAHI

The hygiene standard for pig livestock in Germany is at a medium level as data from the current study show. This applies to the main production systems breeding sow keepers, piglet breeders as well as fattening pig keepers and in relation to continuous (CAHI) and more structural (TAHI) biosecurity measures. With the highest values for the CAHI being 74% (PB; 71% = FPK, 61% = BSK) and for the TAHI being 71% (PB; 67% = FPK, 64% = BSK), results allow the conclusion that an increase of the farms' hygiene level is not only possible but also strongly recommended. Our results are in a similar range as results from Backhans et al. (5). These authors estimated biosecurity levels for farrow-to-finish herd farmers having reached 59–68 points on an average of a possible 100 for hygiene measure implementation.

Piglet breeders had the highest animal hygiene indexes, which could indicate increased awareness of hygienic practices and biosecurity during the very sensitive rearing period where piglets are prone to infectious diseases. The CAHI lead to measures, such as cleaning and disinfection procedures, being implemented more often. These measures lead to better pigs and piglet health (2, 28).

The CAHI seemed to be more important for sow keepers in comparison to fattening pig keepers. This suggests that sow keepers were more aware of the negative consequences when measures are not implemented than fattening pig keepers. Fertilization, birth and rearing periods are sensitive periods, which critically decide about the farms' economic success, too.

Additionally, further analyses have to be done to evaluate in which compartments the greatest deficits and potentials for improvement occurred to specifically target these farm-designed aspects. This should be done separately for every production system. On the other hand, it was difficult to attempt a total and detailed evaluation of the biosecurity level of the pig farms. Hygiene comprises many fields with its measurement of hygiene epidemics as well as hygiene within stable surfaces, water, air and feed [production, storage and its usage; (3)]. Still, the applied "intensive farm questionnaire" with at least 100 queried measures has included many important categories regarding important hygienic measures.

All items were evaluated by three agricultural researchers. This procedure was used for weighting the importance of single items. As such, it should be obvious that "Are further livestock animals kept at this location?" and "Is there a separating area for ill pigs within the stable?" have different weighting factors. The factor 1 (low factor loading) was chosen for the first and factor 3 (high factor loading) for the latter example item. An example for medium factor loading (i.e., factor 2) is "How long does the stable remain empty after cleaning and/or disinfection until its occupancy?" To conclude, clustering of single hygiene measures into indexes offers advantages in the evaluation of pig livestock farm situations.

Big Five Personality Traits and the CAHI and the TAHI

Consideration of pig livestock farmers' personality traits opens new avenues of inquiry to include individuality of farmers more systematically in consulting processes of improving biosecurity in livestock production. The present results from the big-five models gave only weak hints as being related to biosecurity levels as measured by the two index values (CAHI, TAHI). In that way, results showed that conscientiousness and openness had significant impact concerning the CAHI as well as the TAHI. However, this appeared only for fattening pig breeders in respect to both indexes related to conscientiousness. Studies on work performance generally showed significant positive influence of conscientiousness from previous years [reviewed by (48)].

Breeding sow keepers achieved significantly higher values concerning the TAHI if openness was valued higher by self-rating procedures. Consequently, more open sow-keeping farmers tend to have more success in technical measures. This occurrence may be due to a greater inclination toward new techniques and a more digitalized workflow (e.g., from the current questionnaire: "Is a sensor-controlled feed trough implemented?"). Research showed for example that knowledge led farmers to use estrus detection techniques more often with dairy cattle (17). It can be concluded that more open farmers tend to have more interest in increasing their knowledge in this field. The result suggests that veterinarians and farm advisors have to develop strategies to specifically target farmers with lower levels in conscientiousness and openness.

Extraversion had a negative influence on the TAHI in respect to the other-rating with piglet breeders. This personality trait playing a direct role in social interaction in the advisory process might function as a mediating factor (49, 50). This research gap should be addressed in future studies. If these results could be further confirmed, knowledge of improved consulting processes should be transferred to veterinarians as well as farm advisors to meet requirements for successful consulting processes.

Advisory agents should significantly increase their efforts for understanding factors which lead farmer' decisions and behavior. First, it can be emphasized that understanding farmers' decision making and attitudinal behavior are worldwide obstacles to the common urgency of enhancing the biosecurity levels of livestock farms. Secondly, it can be considered that consideration of farmers' personality could improve biosecurity measures and animal health.

LIMITATIONS OF THE STUDY

The present study aimed to analyze if the implementation of hygiene measures correlates with personality traits of intensive pig famers. The sample size of $N = 42$ can be considered limited and is not representative in a statistical sense. Collection of high-quality data about on-farm implementation of hygiene measures as well as data about personality traits require a trust-relation with farmers in the research process. Therefore, a certain tradeoff can be assumed between sample size and data quality. The results of the present study should not be generalized. Instead, they should be considered as a starting point for broader, more comprehensive studies about the link between implementation of hygiene measures in pig farming and the decision-makers in this process.

Moreover, a multidisciplinary approach should be employed to acquire valid and applicable recommendations for veterinarians and farm advisors, including psychologists, social researchers as well as animal scientists. A broader analytical perspective should also include a socio-political understanding of what is involved in changing practices. Hence, it becomes clear that the inclusion of big-five personality traits constitute only a partial explanation of the implementation of biosecurity measures, which has to be complemented by other factors (51, 52).

CONCLUSION

For prevention of zoonotic disease spreading from German pig livestock farms, increased animal hygiene is essential. The underlying hypothesis for the present study was that intensive pig farms' biosecurity levels were influenced by farmers' personalities. As a conclusion from the present data, personality could be considered in advisory processes as one aspect among many. The results should be validated in larger, more representative samples with adapted survey tools. Moreover, future research should be done with respect to a multidisciplinary approach to include multifactorial-caused decision making and attitudinal behavior of livestock farmers.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

Local/national legislation does not require written approval of survey respondents. Verbal consent was acquired at the beginning of each interview. Approval of an ethic committee is not required for the study type.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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REFERENCES

1. Blaha T. *Animal Hygiene as Integral Part of Animal Husbandry or the Growing Power of Hygeia*. Vienna: XV ISAH Congress; Publisher: Tribun EU s.r.o (2011).
2. Heinonen M, Gröhn YJ, Saloniemi H, Eskola E, Tuovinen VK. The effect of health classification and housing and management of feeder pigs on performance and meat inspection findings of all-in-all-out swine-finishing herds. *Prev Vet Med*. (2001) 49:41–54. doi: 10.1016/S0167-5877(01)00175-1

3. Delabbio J. How farm workers learn to use and practice biosecurity. *JOE*. (2006) 44:6FEA1.
4. Racicot M, Venne D, Durivage A, Vaillancourt JP. Evaluation of the relationship between personality traits, experience, education and biosecurity compliance on poultry farms in Quebec, Canada. *Prev Vet Med*. (2012) 103:201–7. doi: 10.1016/j.prevetmed.2011.08.011
5. Backhans A, Sjölund M, Lindberg A, Emanuelson U. Biosecurity level and health management practises in 60 Swedish farrow-to-finish herds. *Acta Vet Scand*. (2015) 57:14. doi: 10.1186/s13028-015-0103-5
6. Delpont M, Blondel V, Robertet L, Duret H, Guerin J-L, Vaillancourt J-P, et al. Biosecurity practices on foie gras duck farms, Southwest France. *Prev Vet Med*. (2018) 158:78–88. doi: 10.1016/j.prevetmed.2018.07.012
7. De Balogh K, Otto P, Mascitelli L, Zingeser J, Burgos-Cáceres S, Lubroth J. A *Glance Into the Future of the Veterinary Public Health Professionals in an Increasingly Threatened World*. Vienna: XV ISAH Congress; Tribun EU s.r.o (2011).
8. Wieland B, Dhollander S, Salman M, Koenen F. Qualitative risk assessment in a data-scarce environment: A model to assess the impact of control measures on spread of African Swine Fever. *Prev Vet Med*. (2011) 99:4–14. doi: 10.1016/j.prevetmed.2011.01.001
9. Dahms C, Hübner N-O, Cuny C, Kramer A. Occurrence of Methicillin-resistant *Staphylococcus aureus* in farm workers and the livestock environment in Mecklenburg-Western Pomerania, Germany. *Acta Vet Scand*. (2014) 56:53. doi: 10.1186/s13028-014-0053-3
10. Cuny C, Nathaus R, Layer F, Strommenger B, Altmann D, Witte W. Nasal colonisation of humans with Methicillin-resistant *Staphylococcus aureus* (MRSA) CC398 with and without exposure to pigs. *PLoS ONE*. (2009) 4:e6800. doi: 10.1371/journal.pone.0006800
11. Köck R, Harlizius J, Bressan N, Laerberg R, Wieler LH, Witte W, et al. Prevalence and molecular characteristics of Methicillin-resistant *Staphylococcus aureus* MRSA among pigs on German farms and import of livestock-related MRSA into hospitals. *Eur J Clin Microbiol Infect Dis*. (2009) 28:1375–82. doi: 10.1007/s10096-009-0795-4
12. White GD, Zhao S, Sulder R, Ayers S, Friedman S, Chen S, et al. The isolation of antibiotic-resistant salmonella from retail ground meats. *N. Engl. J. Med*. (2001) 345:1147–54. doi: 10.1056/NEJMoa010315
13. Helke KL, McCrackin MA, Galloway AM, Poole AZ, Salgado CD, Marriott BP. Effects of antimicrobial use in agricultural animals on drug-resistant foodborne salmonellosis in humans: a systematic literature review. *Crit Rev Food Sci Nutr*. (2017) 57:472–88. doi: 10.1080/10408398.2016.1230088
14. Pesciaroli M, Cucco L, De Luca S, Massacci FR, Maresca C, Medici L, et al. Association between pigs with high caecal Salmonella loads and carcass contamination. *Int J Food Microbiol*. (2017) 242:82–6. doi: 10.1016/j.ijfoodmicro.2016.11.021
15. BfR *An Krankheitsausbrüchen beteiligte Lebensmittel in Deutschland*. Informationen Nr. 030/2014 (2010-2014). Berlin.
16. Vaarst M, Paarup-Laursen B, Houe H, Fossing C, Andersen HJ. Farmers' choice of medical treatment of mastitis in Danish dairy herds based on qualitative research interviews. *J Dairy Sci*. (2002) 85:992–1001. doi: 10.3168/jds.S0022-0302(02)74159-3
17. Garforth C, McKemey K, Rehman T, Tranter R, Cooke R, Park J, et al. Farmers' attitudes towards techniques for improving oestrus detection in dairy herds in South Est England. *Livestock Sci*. (2006) 103:158–68. doi: 10.1016/j.livsci.2006.02.006
18. Garforth C, Rehman T, McKemey K, Tranter R, Cooke R, Yates C, et al. Improving the design of knowledge transfer strategies by understanding farmer attitudes and behaviour. *J Farm Manag*. (2004) 12:17–32.
19. Kuiper D, Jansen J, Renes RJ, Leeuwis C, van der Zwaag H. Social factors related to mastitis control practises: the role of dairy farmers' knowledge, attitude, values, behaviour and networks. *Mastitis Dairy Prod*. (2005) 576–82. doi: 10.3920/978-90-8686-550-5
20. Heffernan C, Nielsen L, Thomson K, Gunn G. An exploration of the drivers to bio-security collective action among a sample of UK cattle and sheep farmers. *Prev Vet Med*. (2008) 87:358–72. doi: 10.1016/j.prevetmed.2008.05.007
21. Gunn GJ, Heffernan C, Hall M, McLeod A, Hovi M. Measuring and comparing constraints to improved biosecurity amongst GB farmers, veterinarians and the auxiliary industries. *Prev Vet Med*. (2008) 84:310–23. doi: 10.1016/j.prevetmed.2007.12.003
22. Klerkx L, Jansen J. Building knowledge systems for sustainable agriculture: Supporting private advisors to adequately address sustainable farm management in regular service contacts. In: *9th European IFSA Symposium 2010*. Vienna (2010). doi: 10.3763/ijas.2009.0457
23. Alarcon P, Wieland B, Mateus ALP, Dewberry C. Pig farmers' perceptions, attitudes, influences and management of information in the decision-making process for disease control. *Prev Vet Med*. (2014) 1163:223–42. doi: 10.1016/j.prevetmed.2013.08.004
24. Wauters E, Rojo-Gimeno C. *Socio-Psychological Veterinary Epidemiology. A New Discipline for an Old Problem*. Dublin: Society for Veterinary Epidemiology and Preventive Medicine (2014).
25. Wappenar W, Wappenar A, Simon C, Remnant JG, Murphy A. Control of infectious diseases in dairy cattle. In: *Achieving Sustainable Production of Milk*. Cambridge: Burleigh Dodd Science Publishing (2017). p. 457–486. doi: 10.19103/AS.2016.0006.23
26. Renault V, Humblet MF, Moons V, Bosquet G, Gauthier B, Cebrián ML, et al. Rural veterinarian's perception and practices in terms of biosecurity across three European countries. *Transbound Emerg Dis*. (2018) 65:e183–93. doi: 10.1111/tbed.12719
27. Vaarst M, Sørensen JT. Danish dairy farmers' perceptions and attitudes related to calf-management in situations of high versus no calf mortality. *Prev Vet Med*. (2009) 89:128–33. doi: 10.1016/j.prevetmed.2009.02.015
28. Ravel A, D'Allaire S, Bigras-Poulin M. Influence of management, housing and personality of the stockperson on preweaning performances on independent and integrated swine farms in Québec. *Prev Vet Med*. (1996) 29:37–57. doi: 10.1016/S0167-5877(96)01053-7
29. Edwards-Jones G, Deary I, Willock J. Incorporating psychological variables in models of farmer behaviour: does it make for better predictions? *Etudes Recherches Systèmes Agraires Dêveloppement*. (1998) 153–73.
30. Hansson H, Lagerkvist CJ, Vesala KM. Impact of personal values and personality on motivational factors for farmers to work with farm animal welfare: a case of Swedish dairy farmers. *Animal Welf*. (2018) 27:133–45. doi: 10.7120/09627286.27.2.133
31. Allport GW. *Personality: A Psychological Interpretation*. Oxford: Holt (1937).
32. Saucier G, Goldberg LR. The language of personality: lexical perspectives on the five-factor model. In: Wiggins JS, editor. *The Five-Factor Model of Personality, Theoretical Perspectives*. New York, NY; London: The Guilford Press (1996). p. 21–50.
33. Stern W. *Die differentielle Psychologie in ihren methodischen Grundlagen. 3. Auflage*. Leipzig: Johann Ambrosius Barth (1921).
34. Eysenck HJ. *Dimensions of Personality*. Oxford: Kegan Paul, Trench, Trubner and Co., Ltd (1947).
35. Austin EJ, Deary IJ, Willock J. Personality and intelligence as predictors of economic behaviour in Scottish farmers. *Eur. J. Pers*. (2001) 15:S123–37. doi: 10.1002/per.421
36. Sok J, Hogeveen H, Elbers ARW, Oude Lansink AGJM. Perceived risk and personality traits explaining heterogeneity in Dutch dairy farmers' beliefs about vaccination against Bluetongue. *J Risk Res*. (2016). 21:562–78. doi: 10.1080/13669877.2016.1223162
37. O'Kane H, Ferguson E, Kaler J, Green L. Associations between sheep farmer attitudes, beliefs, emotions and personality, and their barriers to uptake of best practice: The example of foot rot. *Prev Vet Med*. (2017) 139:123–33. doi: 10.1016/j.prevetmed.2016.05.009
38. Schupp J, Gerlitz J-Y. *Big Five Inventory-SOEP (BFI-S)*. Mannheim: Zusammenstellung sozialwissenschaflicher Items und Skalen (2014). doi: 10.6102/zis54
39. Wildraut C, Freitag H, Boelhauve M, Mergenthaler M. *Teilnahmeintensität von Landwirten an einem Hygieneprojekt in der Schweinehaltung in NRW ist weitgehend unabhängig von Betriebs- und Betriebsleitermerkmalen*. Notizen aus der Forschung Nr. 5/2017. Soest: Fachbereich Agrarwirtschaft (2017).
40. Hecker OC, Boelhauve M, Mergenthaler M. Start-up financing of professional pest control in pig farming in North Rhine-Westphalia in Germany. *Porcine Health Manag*. (2018) 4:22. doi: 10.1186/s40813-018-0099-0
41. Lang FR, Hahne D, Gymbel S, Schröpper S, Lutsch K. Erfassung des kognitiven Leistungspotenzials und der 'Big Five' mit Computer-Assisted-Personal-Interviewing (CAPI): Zur Reliabilität und Validität zweier ultrakurzer Tests und des BFI-S. *DIW Res Notes*. (2005) 9:2005.

42. Connelly BS, Ones DS. Another perspective on personality: Meta-analytic integration of observers' accuracy and predictive validity. *Psychol Bull*. (2010) 136:1092–122. doi: 10.1037/a0021212
43. Vazire S. Who knows what about a person? The self-other knowledge asymmetry SOKA model. *J Pers Soc Psychol*. (2010) 98:281–300. doi: 10.1037/a0017908
44. Barrick MR, Mount MK, Judge TA. Personality and performance at the beginning of the new millennium: What do we know and where do we go next? *Int J Sel Assess*. (2001) 9:9–30. doi: 10.1111/1468-2389.00160
45. Saucier G. Recurrent personality dimensions in inclusive lexical studies: indications for a big six structure. *J Pers*. (2009) 77:1577–614. doi: 10.1111/j.1467-6494.2009.00593.x
46. Thalmayer AG, Saucier G, Eigenhuis A. Comparative validity of brief to medium-length Big Five and Big Six personality questionnaires. *Psychol Assess*. (2011) 234:995. doi: 10.1037/a0024165
47. Thalmayer AG, Saucier G. The questionnaire big six in 26 nations: developing cross-culturally applicable big six, big five and big two inventories. *Eur J Pers*. (2014) 285:482–96. doi: 10.1002/per.1969
48. Barrick MR, Mount MK. The Big five personality dimensions and job performance: A meta-analysis. *Pers Psychol*. (1991) 44:1–26. doi: 10.1111/j.1744-6570.1991.tb00688.x
49. Mount MK, Barrick MR, Stewart GL. Five-Factor model of personality and performance in jobs involving interpersonal interactions. *Hum Perform*. (2011) 11:145–65. doi: 10.1080/08959285.1998.9668029
50. Smith MA, Canger JM. Effects of supervisor 'Big Five' personality on subordinate attitudes. J Bus Psychol. (2004) 18:465–81. doi: 10.1023/B:JOBU.0000028447.00089.12
51. Garforth CJ, Bailey AP, Tranter RB. Farmers' attitude to disease risk management in England: a comparative analysis of sheep and pig farmers. *Prev Vet Med*. (2013) 110:456–66. doi: 10.1016/j.prevetmed.2013.02.018
52. Hektoen L. Investigations of the motivation underlying Norwegian diary farmers' use of homoeopathy. *Vet Rec*. (2004) 155:701–7. doi: 10.1136/vr.155.22.701

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