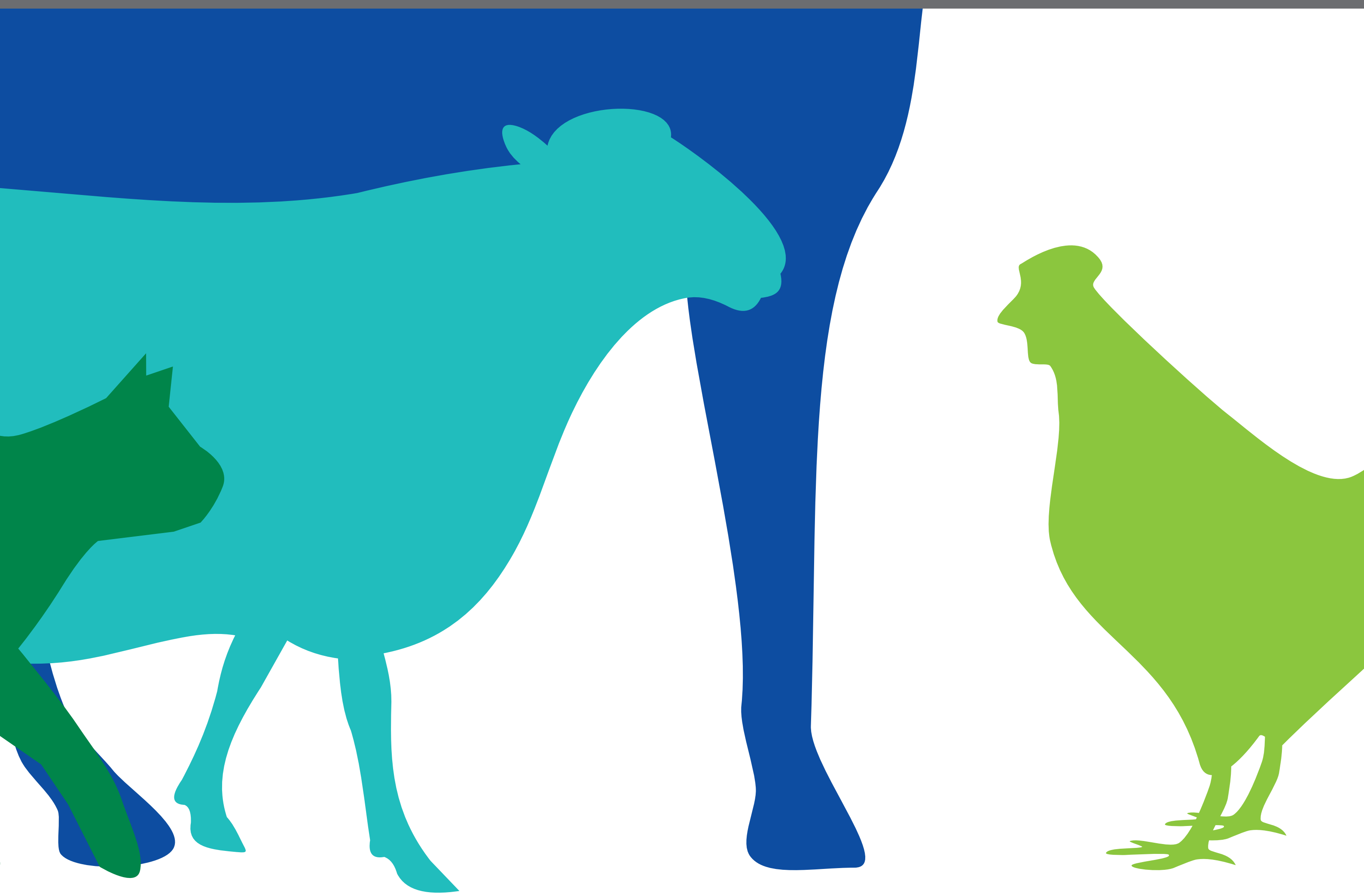
BRIDGING SCIENCE AND POLICY FOR SURVEILLANCE, ECONOMICS AND SOCIAL SCIENCES: ICAHS & ISESSAH 2020

EDITED BY: Carola Sauter-Louis, Lis Alban, Victoria J. Brookes, Victor Javier Del Rio Vilas, Salome Dürr, Chris J. M. Bartels, Bouda Vosough Ahmadi and Jonathan Rushton

PUBLISHED IN: Frontiers in Veterinary Science



frontiers Research Topics

ISSN 1664-8714
ISBN 978-2-88974-017-8
DOI 10.3389/978-2-88974-017-8

About Frontiers

Frontiers is more than just an open-access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers Journal Series

The Frontiers Journal Series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the Frontiers Journal Series operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to Quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews.
Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the Frontiers Journals Series: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area! Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers Editorial Office: frontiersin.org/about/contact

BRIDGING SCIENCE AND POLICY FOR SURVEILLANCE, ECONOMICS AND SOCIAL SCIENCES: ICAHS & ISESSAH 2020

Topic Editors:
Carola Sauter-Louis, Friedrich-Loeffler-Institute, Germany
Lis Alban, Danish Agriculture and Food Council, Denmark
Victoria J. Brookes, The University of Sydney, Australia
Victor Javier Del Rio Vilas, Pan American Health Organization, United States
Salome Dürr, University of Bern, Switzerland
Chris J. M. Bartels, Animal Health Works, Netherlands
Bouda Vosough Ahmadi, European Commission for the Control of Foot and Mouth Disease (EuFMD), Italy
Jonathan Rushton, University of Liverpool, United Kingdom

Topic Editor Lis Alban works for an organization that gives advice to farmers and abattoirs. All other Topic Editors declare no competing interests with regard to the Research Topic subject.

Citation: Sauter-Louis, C., Alban, L., Brookes, V. J., Vilas, V. J. D. R., Dürr, S., Bartels, C. J. M., Ahmadi, B. V., Rushton, J., eds. (2021). Bridging Science and Policy for Surveillance, Economics and Social Sciences: ICAHS & ISESSAH 2020. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-88974-017-8

Table of Contents

frontiers in Veterinary Science

EDITORIAL
published: 18 November 2021
doi: 10.3389/fvets.2021.790248

Editorial: Bridging Science and Policy for Surveillance, Economics and Social Sciences: ICAHS and ISESSAH 2020

Lis Alban[1,2]*, *Carola Sauter-Louis*[3], *Victoria J. Brookes*[4], *Chris J. M. Bartels*[5], *Bouda Vosough Ahmadi*[6], *Jonathan Rushton*[7] *and Salome Dürr*[8]

[1] Danish Agriculture and Food Council, Copenhagen, Denmark, [2] Department of Veterinary and Animal Sciences, University of Copenhagen, Copenhagen, Denmark, [3] Institute of Epidemiology, Friedrich-Loeffler-Institute, Greifswald, Germany, [4] Sydney School of Veterinary Science, University of Sydney, Camperdown, NSW, Australia, [5] Food and Agricultural Organization, Ulaanbaatar, Mongolia, [6] The European Commission for the Control of Foot and Mouth Disease (EuFMD), Animal Production and Health Division (NSA), Food and Agricultural Organization, Rome, Italy, [7] Veterinary and Ecological Sciences, Faculty of Health and Life Sciences, Institute of Infection, University of Liverpool, Liverpool, United Kingdom, [8] Veterinary Public Health Institute, Vetsuisse Faculty, University of Bern, Bern, Switzerland

Keywords: animal health, zoonoses, food safety, epidemiology, economics, surveillance

Editorial on the Research Topic

Bridging Science and Policy for Surveillance, Economics and Social Sciences: ICAHS and ISESSAH 2020

OPEN ACCESS

Edited and reviewed by:
Andres M. Perez,
University of Minnesota Twin Cities, United States

***Correspondence:**
Lis Alban
lia@lf.dk

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: 06 October 2021
Accepted: 22 October 2021
Published: 18 November 2021

Citation:
Alban L, Sauter-Louis C, Brookes VJ, Bartels CJM, Vosough Ahmadi B, Rushton J and Dürr S (2021) Editorial: Bridging Science and Policy for Surveillance, Economics and Social Sciences: ICAHS and ISESSAH 2020. Front. Vet. Sci. 8:790248. doi: 10.3389/fvets.2021.790248

African swine fever, antimicrobial resistance and the release of zoonotic pathogens from food systems are examples of three global challenges in animal health, which are currently threatening the world. These hazards are associated with significant economic, societal and food security issues for a growing number of countries. The movement of people, animals and food has increased to a point where major disease events are occurring with increased frequency, challenging our ability to manage these problems in a timely and proportionate manner. Until better animal health surveillance and associated response measures are adequately resourced, the challenge society faces will continue to grow. The COVID-19 pandemic indicates that simply acting on emergence and spread is not appropriate. Preparedness is warranted to prevent, detect and control outbreaks before they become large.

In the process of preventing and mitigating the risks and impacts of these challenges, surveillance is a key element. It enables an understanding of the actions needed - for example, why and where actions are required. The social, economic and cultural context needs to be understood for the implemented mitigating actions to have the greatest probability of success in the prevention and control of animal and zoonotic threats.

Available solutions are dynamic because they are influenced by the societies affected and their associated side-effects, such as constraints on trade and food security. Moreover, what is considered feasible in one country might not be feasible in another, or it might be considered not worth doing by decision-makers because other surveillance options or challenges are perceived as more important. Learning from and sharing each other's experiences are therefore pivotal for successful control and mitigation of cross-border challenges. Hence, the actors involved in surveillance and control - whether they are affiliated with government authorities, academia or livestock industries - need to exchange views and experience to be able to collaborate effectively in a transdisciplinary way. In the future, this may result in the development of new ways of collaboration using cross-sectoral and interdisciplinary approaches such as through Public-Private-Partnerships. Much can probably be obtained through such alternative governance models - if people know how to do it.

The International Conference on Animal Health Surveillance (ICAHS) and The International Society for Economics and Social Sciences of Animal Health (ISESSAH) provide an opportunity for learning and sharing between academic researchers, representatives of the food supply chain, authorities, as well as people working for international organizations within food safety and food security, and animal health from all over the world. Although the joint conference planned in May 2020 was canceled due to the COVID-19 pandemic, the authors of research which were selected to be part of the joint ICAHS4/ISESSAH conference were invited to submit their work to this Research Topic. The areas covered include the following topics, identified by the international Scientific Committee for the ICAHS4 and ISESSAH conference:

- Integrating novel methods in surveillance
- Use of surveillance data
- Cross-sector surveillance – organization, collaboration and benefits
- Translating surveillance outcomes into policy, decisions and actions
- Costs and motivation
- Social science in the control of animal diseases
- Economic considerations in animal health

The Research Topic consists of 16 papers of which three were brief research reports and 13 original research articles. The papers report work undertaken in Africa, Australia, Europe, Southeast Asia, as well as South- and North America. Fish, chickens, pigs, sheep, bovines, horses as well as ungulates as a group were the livestock species studied. The specific hazards were Classical and African Swine Fever, Foot-and-Mouth Disease, *Salmonella*, Psoroptes ovis causing sheep scab, antimicrobial use (AMU) and resistance (AMR), *Vibrio* as well as One Health and zoonotic infections in general.

Regarding integrating novel methods in surveillance, Sandberg et al. report from an ongoing scientific network project called CoEvalAMR dealing with how to assess evaluation tools for AMU and AMR. The authors conclude that there are many tools available which each have their advantages and disadvantages, making it pertinent to choose a method which fits the objective of evaluation.

Three papers describe the use of surveillance data. The first by Desvaux et al., reports an analysis of the effect of strengthened surveillance to support African Swine Fever prevention in France at the border of Belgium during the outbreak of African Swine Fever in Belgium. The objective of the strengthened surveillance was to assure early detection and to support the free status of the zone. Tuat et al. report from a pilot surveillance programme for AMR in pigs and chickens in Vietnam, enabling them to map the prevalence of different kinds of AMR. The authors conclude that establishment of an annual surveillance programme for AMR in livestock is needed in Vietnam. Finally, Veldhuis et al. investigated the added value of meat inspection data for monitoring of dairy cattle health in the Netherlands. Seven indicators were judged to add value to the existing cattle health surveillance components, as they provided either new information or information regarding specific health problems.

Two papers describe cross-sector surveillance–organization, collaboration and benefits. The first is by Thomas et al., who studied the cross-sectoral zoonotic disease surveillance in place in Western Kenya using interviews with 28 disease surveillance officers from the human and animal health sectors. The study points to the challenges related to the lack of formal operational structures and poor allocation of resources. Schettino et al. have undertaken a risk assessment regarding the introduction of Classical Swine Fever into Mato Grosso in Brazil. The authors identified two major pathways; the first dealt with shipment of commercial pigs and the other with movement of wild boars. The conclusion was that the strategies for surveillance must target the specific route of entry.

Translation of surveillance outcomes into policy, decisions and actions is covered by three papers. The first of these is by Geddes et al., who investigated how scanning surveillance can be used to inform future strategies for the control of endemic diseases, using sheep scab as an example. The work undertaken led to an enhancement of the knowledge of sheep scab, identified areas for targeted action, and offered a framework for assessment of impact of disease control initiatives. The second paper is by Capon et al., who in a simulation study assessed the use of vaccination against Foot-and-Mouth Disease outbreaks across Australia. Several scenarios were investigated. The conclusion was that selective, targeted vaccination strategies could achieve effective control, while significantly reducing the number of animals vaccinated. The third paper is by Dórea and Revie, who reviewed the opportunities for connecting data and generating information to support decision-making. The authors focus on the challenges related to the increasingly complex dimensions of data in population health, and how to enable data-driven surveillance to go beyond signal detection and support an expanded set of surveillance goals.

Two papers deal with costs and motivation. The first is by Olsen et al., who studied Danish pig farmers' perceptions of the existing economic incentives to control *Salmonella* prevalence at herd level. The results support the idea of an outcome-based *Salmonella* penalty scheme that is presently in place. However, the large uncertainties about costs and effects toward *Salmonella* control might hamper the effectiveness of the penalty system as a regulatory instrument to influence farmer behavior. The second paper is by Urner et al., who investigated the perceptions of Estonian and Latvian hunters regarding the control of African Swine Fever. There were mainly similarities in hunters' perceptions between the two countries, although the passive surveillance in Latvia was perceived more as an ethical duty than driven by incentives. The results highlight further opportunities for improving the cooperation with hunters in the future.

Aspects related to social science in the control of animal diseases are covered in three papers. The first of these is by Pudenz et al., who studied US cattle producers' adoption of the Secure Beef Supply Plan, which is focusing on enhancing biosecurity practices and preparedness for Foot-and-Mouth Disease. The authors found that the adoption of the pre-outbreak practices is likely to be low because the benefits of adopting the practices depend on an event, which is associated with a low and uncertain probability. Özçelik et al. investigated the potential and challenges of community-based surveillance in animal health, using a pilot study among equine owners in Switzerland. The ambition was to assess the use of community members other than health care professionals for reporting health events. One conclusion is that it is questionable whether the added value of the generated surveillance balances the efforts necessary to implement a successful system. Finally, Bordier et al. studied how to engage stakeholders in the design of One Health surveillance systems through a participatory approach. The study was undertaken in Vietnam and in France. It identified that the engagement of the stakeholders in a participatory process must be sustained to ensure the implementation of co-constructed solutions and to evaluate their effectiveness and impacts.

Economic considerations in animal health are covered in two papers. Yazid et al. estimated the economic loss due to vibriosis in net-cage cultured Asian seabass. The case was based on evidence from the East coast of the Malaysian peninsular. Asian seabass production has contributed substantially to Malaysia's economic activities and food security. It is concluded that more focus is needed regarding control and prevention of vibriosis infection from the hatcheries. Vredenberg et al. made an empirical analysis of the longevity of dairy cows in relation to economic herd performance, using data from the Netherlands. The results show that the gross margin was not significantly associated with the age of the culled cows or lifetime milk production of culled cows. Moreover, the authors conclude that this implies that there is a potential for increasing longevity to meet society's concerns on animal welfare and environmental pollution without affecting the economic performance of the herd.

AUTHOR CONTRIBUTIONS

LA took the lead in writing the Editorial and received comments from the co-authors. All authors of the editorial contributed as editors to the production of the research theme.

Conflict of Interest: LA works for an organization that gives advice to the Danish farmers and meat industry.

The remaining 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.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Veterinary Science

BRIEF RESEARCH REPORT
published: 12 March 2021
doi: 10.3389/fvets.2021.633977

Data-Driven Surveillance: Effective Collection, Integration, and Interpretation of Data to Support Decision Making

Fernanda C. Dórea[1]* *and Crawford W. Revie*[2]

[1] *Department of Disease Control and Epidemiology, National Veterinary Institute, Uppsala, Sweden,* [2] *Computer and Information Sciences, University of Strathclyde, Glasgow, United Kingdom*

The biggest change brought about by the "era of big data" to health in general, and epidemiology in particular, relates arguably not to the volume of data encountered, but to its variety. An increasing number of new data sources, including many not originally collected for health purposes, are now being used for epidemiological inference and contextualization. Combining evidence from multiple data sources presents significant challenges, but discussions around this subject often confuse issues of data access and privacy, with the actual technical challenges of data integration and interoperability. We review some of the opportunities for connecting data, generating information, and supporting decision-making across the increasingly complex "variety" dimension of data in population health, to enable data-driven surveillance to go beyond simple signal detection and support an expanded set of surveillance goals.

Keywords: epidemiology, machine learning, big data, data analyses, linked data

OPEN ACCESS

Edited by:
Lis Alban,
Danish Agriculture and Food Council, Denmark

Reviewed by:
Judy Akkina,
United States Department of Agriculture (USDA), United States
John Berezowski,
University of Bern, Switzerland

****Correspondence:***
Fernanda C. Dórea
fernanda.dorea@sva.se

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: *26 November 2020*
Accepted: *18 February 2021*
Published: *12 March 2021*

Citation:
Dórea FC and Revie CW (2021) Data-Driven Surveillance: Effective Collection, Integration, and Interpretation of Data to Support Decision Making. Front. Vet. Sci. 8:633977. doi: 10.3389/fvets.2021.633977

INTRODUCTION

Increases in data volume, diversity and speed have affected all aspects of human life. As we advance into the 21st century, Simonsen et al. (1) highlight two main streams that are pushing health surveillance into the "Big Data Era": the advancements in laboratorial detection tools which traditional surveillance rely on, and a dramatic increase in the number of health and non-health related data streams that can be exploited for surveillance. However, as Leyens et al. (2) point out, "the simple fact that there is more data is not useful to public health unless we are able to turn it into 'actionable data' for improved health outcomes and more effective and efficient health systems."

While health surveillance systems continue to adapt, improving traditional components [e.g., (2–4)] and adding others based on the exploitation of novel data streams [e.g., (5–8)], their progress fades in comparison to that seen in other sectors (1), from business and marketing to the more related area of diagnostic services within human health. While data scientists seem to agree that a significant big data trend in 2017 was an end to talk about it as if it were a novelty (9), in health surveillance "big data" remains a buzz word. A number of publications have discussed the challenges and potential benefits of incorporating big data into surveillance, but a framework for the operationalization of data-driven surveillance has seldom been discussed. Moreover, discussions around the exploitation of novel data streams has been focused almost exclusively on emergence prediction and early disease detection, in detriment of other surveillance goals, such as situational awareness for non-communicable and endemic diseases, and disease freedom demonstration.

Based on the results of a workshop carried out in late 2017, and supported by a scoping review, we discuss the challenges and opportunities for implementing data-driven surveillance frameworks as a 3-step process: data integration; data processing to generate information; and making outputs from data analyses accessible and usable by decision-makers.

METHODS

On October 10th and 11th, 2017, the Uppsala Heath Summit gathered around 200 delegates from different sectors, and from around the world, to discuss priorities for preventing, detecting and responding to infectious disease threats using a One Health approach (10). A dedicated 3 h workshop was conducted by the authors to explore the theme of innovation and big data in health surveillance. The 63 workshop participants brainstormed to identify and prioritize opportunities to achieve data-driven decision-making in population health, within the One Health context. Participants came from a range of sectors: 16 were from universities, 11 from the private sector, 22 from governmental agencies and one from a global health organization. This was a multi-disciplinary group, from the fields of public health (11), animal health (12), pharmacovigilance (13), health and medicine (3), data science (4), climate (1), and geography (1). Most participants worked in European countries, with three participants from Africa, two from North America and one from South America. Informed by a literature search targeting articles in the health surveillance domain which used the term "big data," workshop discussions were organized into four main groups of "big data analytics" (BDA) challenges: technical, operational, normative (cultural and ethical challenges), and funding. A summary of the workshop discussions, within the four main challenge themes, is already available in the post-conference report (10). Following the workshop, we have organized the discussion according to actual implementation steps, laying out a "data to actionable information" continuum, and enriched it with bibliography relevant for each section.

We have also updated and reviewed the literature search specifically targeting BDA. We searched Scopus for papers published up to December 2020 in the general area of health surveillance which contained the term "big data" [TITLE-ABS-KEY ("big data" AND surveillance AND (health OR disease OR syndromic))]. This search returned 492 papers. After reviewing title and abstract, and reading selected papers for which full-text was available in English, we selected a total of 47 papers which specifically discuss data science and data innovation challenges and opportunities in any area of health surveillance.

We have not cited all papers here due to space limitations, but the full list of 44 selected papers is available in the **Supplementary Material**, and also at (http://datadrivensurveillance.org/dds_ICAHS2020).

RESULTS AND DISCUSSION

Step 1—Connecting Data

The most significant changes in the area of health data in general, and epidemiology in particular, arguably relate not to the volume of data, but to their variety. An increasing number of innovative data sources, including many not collected specifically for health purposes, can now be used for epidemiological inference and contextualization (14). The challenges of data integration have been discussed by many researchers (2, 12, 13, 15, 16). Often, however, the discussion confuses issues around data access and privacy, with the actual technical challenges of data integration and interoperability. The latter issues are central to contemporary surveillance, which increasingly relies on combining evidence from multiple data sources.

Surveillance data have traditionally been classified by mode of acquisition: active or passive. With the advent of "big data," the concept of data acquisition becomes less central—we move from intentionally producing surveillance data, to taking advantage of ubiquitous data sources generated as a part of many processes, health related, or not (11). The technical challenge is no longer validating a dataset in which each observation was intentionally recorded, but rather mining data streams for valid evidence to support decision making (11).

Figure 1 illustrates the potential data streams from which signals of a health hazard occurrence might originate for the case of Schmallenberg virus being introduced into a dairy herd. This figure represents a limited snapshot of the health continuum of interest for animal health. We can imagine the increased complexity involved if we were to consider a zoonotic pathogen, and had to factor in exposure to humans through the food production cycle, or environmental exposure. The variety of novel data streams that can support surveillance has been reviewed in detail for animal health (17, 18), drug safety and health care (2), food safety (19), and one medicine (20). Opportunities associated specifically with spatial data sources (21) and search query data (22) have also been reviewed.

In addition to the access and interpretation of a greater number of opportunistic data sources, there are also increased opportunities to redesign the purposeful collection of surveillance data in the digital era. Salathé (14) discussed applications to drug safety monitoring, while a broader review of crowd-sourcing, citizen sensing and sensor web technologies for health is given by Kamel Boulos et al. (23). Workshop participants highlighted, in particular, the use of apps for patient reporting or self- diagnosis, which can have value along the entire surveillance continuum: from prevention, to communication with the public during response.

The sources of data we have access to determine the types of evidence we can extract, and the timeliness of such extraction. As Han and Drake (24) note, our ability to move toward predictive capacity is limited not by technology, but by access to appropriate data. To achieve a paradigm shift in disease control, moving from disease response to disease intelligence, a resilient health system must be underpinned by environmental, geographic, and population data (2, 24).

During the workshop, the group concluded that the single biggest barrier to gaining insights from data, particularly in real-time settings, was data integration. The need to "break the barriers of siloed data" was often mentioned as a priority. Timely access to integrated data was considered the main challenge

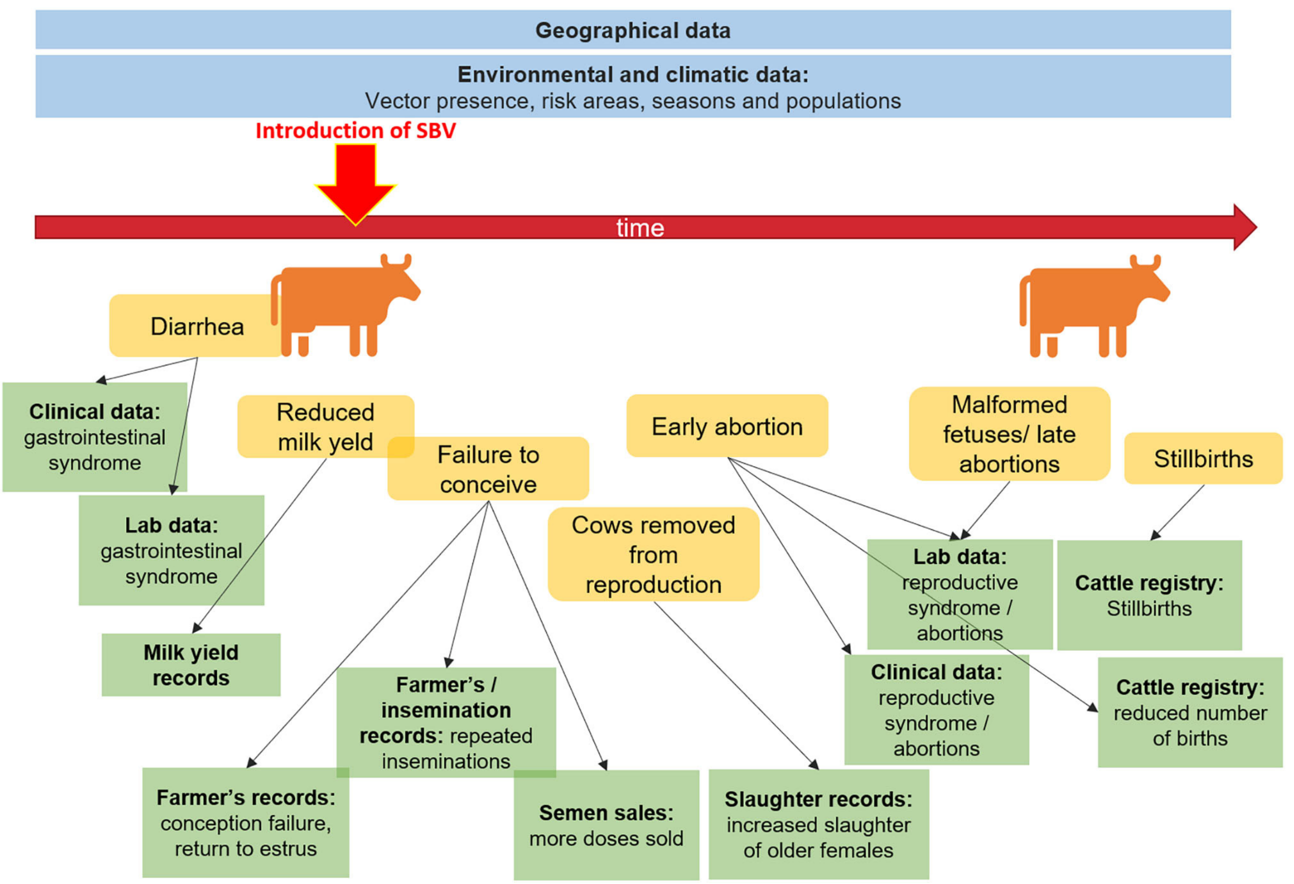


FIGURE 1 | Potential data sources to aid surveillance before and after the introduction of Schmallenberg virus.

to using data-driven evidence in emergencies, such as during outbreak response.

The issue of data integration and interoperability (25) is particularly important when targeting long chains involving multiple actors, such as in food safety surveillance (19). The lack of standardized data was repeatedly mentioned as a barrier for data processing and interpretation. However, as the discussion around this issue matured, most participants agreed that it was unrealistic to expect data standardization, as in fact many standards already exist for health data, but are not used. Most importantly, many existing standards contribute only to achieving structural (*syntactic*) interoperability.

As the secondary use of data sources (re-use) increases, and models demand integration of data from multiple disciplines, we will increasingly require *semantic* interoperability. Semantic interoperability is concerned with ensuring that the integrity and meaning of the data is preserved throughout the integration process (26). This is achieved by storing data in machine interoperable formats making use of knowledge models that explicitly document, for humans and for machines, the domain knowledge and assumptions under which data were collected and are stored (27). Ontologies allow domain experts to create knowledge models that can be interpreted both by humans and machines (28). Using such models, computers can reason with data without relying on the use of specific codification. For an example in animal health, see Dórea et al. (29).

Step 2—Generating Information

A common skepticism related to big data comes from authors who highlight its potential to become a "hypothesis generating machine," capable of detecting correlation, but not causation (12, 30). The question should perhaps not be whether big data are useful, but what they are useful for. In surveillance, associations may be an important source of information for decision on interventions that aim at risk mitigation or case finding, even in the absence of any proven causal association. Iwashyna and Liu (11) point out that the questions which big data cannot answer are similar to those that are also a challenge in most observational studies, such as prescriptive questions. The authors suggest three main types of questions that can be addressed with big data: prognostic questions (what is going to happen), which "require temporally stable associations, not underlying causal models"; predictive questions (what will likely happen if something different is done); and patterning questions (describing population patterns).

Automated access to continuous streams of data has allowed monitoring of population patterns—and early detection of unexpected changes—at earlier and earlier steps on the disease continuum. From direct monitoring of early registers (e.g., veterinarian calls or visits to the emergency room), to even less specific, but earlier signs of health change, such as over-the-counter drug sales. This component has been coined "syndromic surveillance" due to the initial focus on the monitoring of unspecific clinical symptoms in public health (31). The methodology has been applied in animal health to a number of data sources that are not necessarily "syndromic" (32, 33), and its utility is being increasingly explored for situational awareness

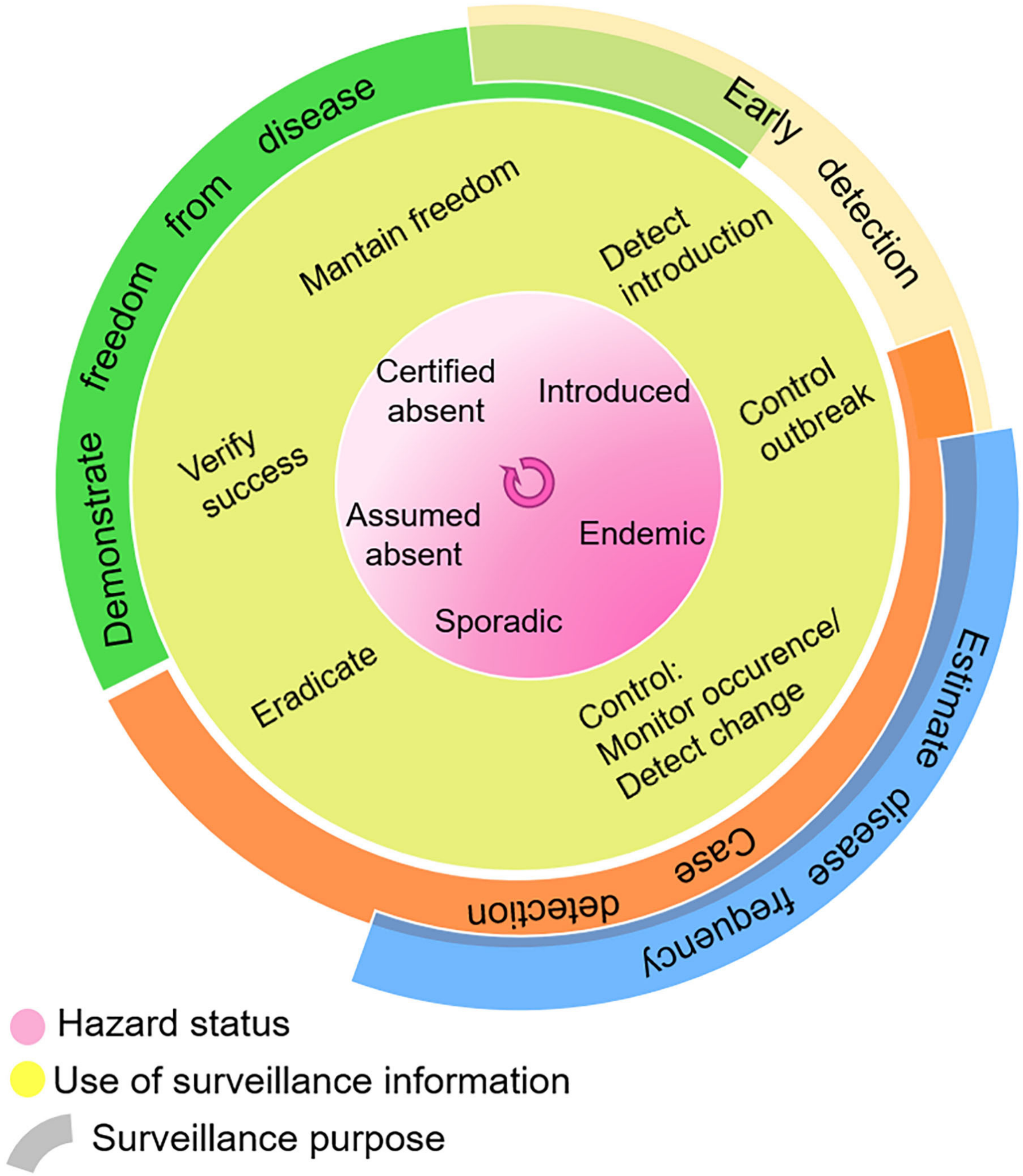


FIGURE 2 | Use of surveillance information in the context of hazard status, and surveillance purpose. Adapted with permission from Linda Hoinville (41).

rather than simply for early disease detection. To that end, Smith et al. (34) reported the need to focus on system sustainability and usefulness as one of the main lessons learned from two decades experience with syndromic surveillance in the UK. They argued that systems should be designed with a focus on the uses, not the data sources, and should aim to serve multiple public health objectives.

For a more complete review of the architectures and specific methods for big data analysis in health surveillance, we refer readers to (19, 25, 35, 36). For a review of the use of terms "big data," "informatics" and "bioinformatics" in the animal health and veterinary medical literature, we refer to (37).

During the workshop, the discussion focused not on what analysis tools to use, but on how to incorporate available methods within routine surveillance. The gap between technological and methodological innovation, as well as implementation in field settings are also discussed in (38). An important message related to the fact that surveillance officials should not only have access to the right tools, but should also be capable of using them effectively. "Efficient people and technology," as one captured note summarized this point. The need for more training was repeatedly listed, in addition to the importance of making tools that are more accessible to domain experts; that is, user-friendly and available in local languages. Chiolero and Buckeridge (39) called these the "knowledge brokers" needed to "bridge data science, health monitoring and public health." Reference was also made to the training needs discussion presented in Brownson et al. (40).

Step 3—Supporting Decision-Making

Surveillance activities are designed according to the desired use of surveillance information, as summarized in **Figure 2**. This in turn depends on the hazard occurrence in the target population or geographical area. As can also be seen in this figure, the boundaries are not always clear, and purposes can overlap. This highlights an overall workshop conclusion that the separation of surveillance goals may be artificial, and that a data-driven decision support system should be designed to strengthen all stages of disease control. Chiolero and Buckeridge (39) emphasize the role of decision-makers in identifying surveillance needs, setting priorities, and evaluating the effect of interventions. They added to their "glossary of public health surveillance in the era of big data" the idea of a continuum from data, to information, to *evidence* (which "emerges from

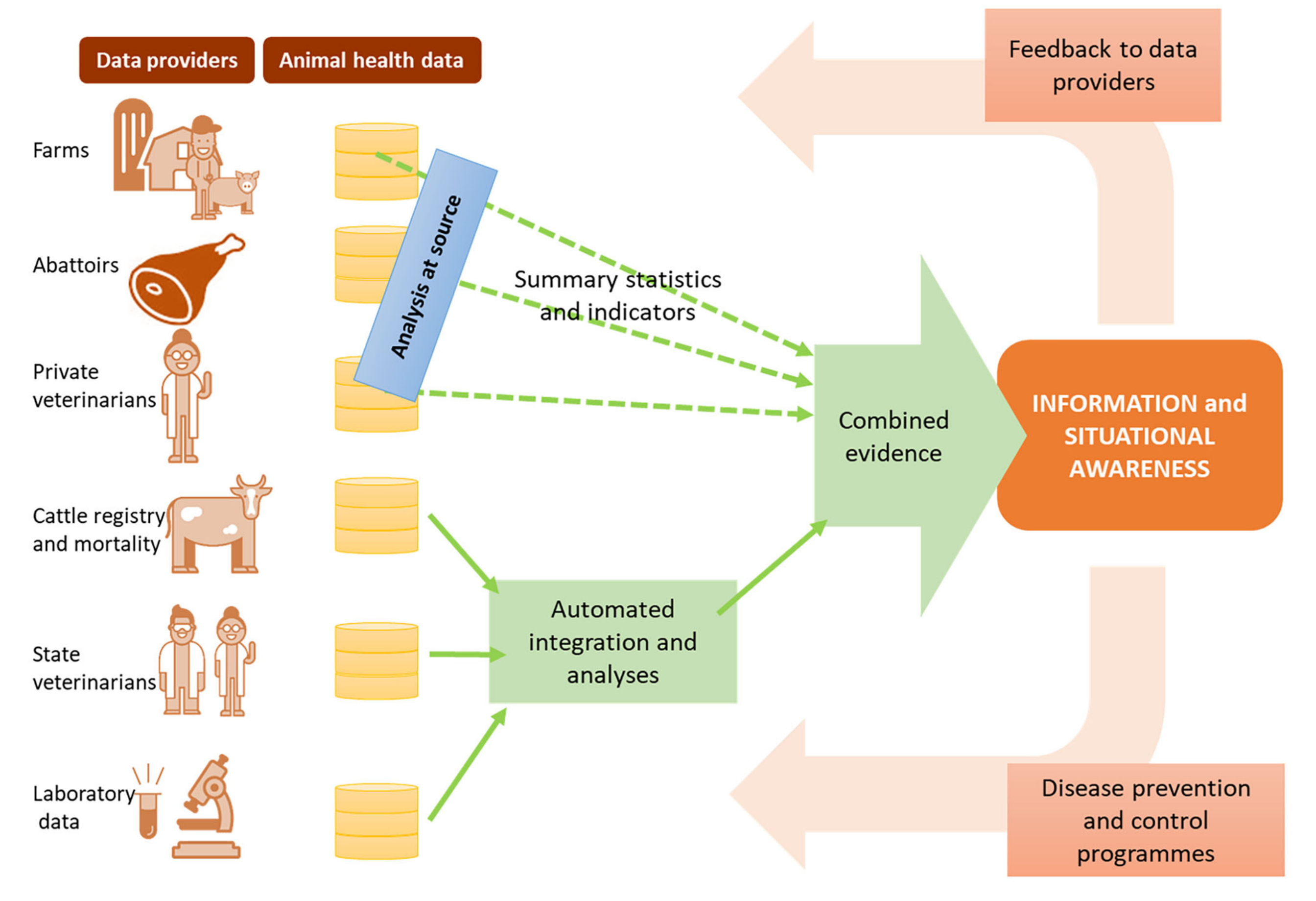


FIGURE 3 | Data-driven surveillance framework being developed in Sweden, as an example of how information and evidence can be produced from multiple data sources without relying on data sharing.

the comparison of information"), then "used to build actionable knowledge" (DIEK pyramid) (42).

Increases in data variety and velocity have opened up new surveillance opportunities, most notably in relation to disease prevention and early detection. The ability to train statistical algorithms on a large quantity and variety of data to identify relationships and monitor interactions allows us to monitor risks in space and time [creating a "riskscape" (24)], and respond to these risks, rather than to occurrence. It creates the opportunity to improve timeliness and population coverage, and increase resolution (spatial and temporal) (25), leading to infectious disease intelligence—knowing what, when, why, and how to respond (24). In public health, the use of new data and technologies to assess population health with increased accuracy and granularity at temporal and geographical levels, delivering programs tailored to specific populations, has been coined "precision public health" (39, 43).

While the advent of "big data analysis" has been extensively discussed for disease prediction and early response, its support to other surveillance goals has often been overlooked. Access to digitalized and novel data streams can increase the timeliness of surveillance information, but can also "improve temporal or spatial resolution of surveillance, add surveillance to places with no existing systems,... measure aspects of a transmission/disease process not captured by traditional surveillance, and increase the population size under surveillance" (44). Antoine-Moussiaux et al. (45) argue that a focus on detection of disease signals may miss the true value of surveillance, which lies in its continuity. They propose that health surveillance should be viewed as an information system, which continuously provides feedback to inform the prioritization of actions.

This assumes we have addressed the two previous steps, and as such have access not simply to "big data," but to FAIR data—findable, accessible, interoperable and reusable (46). In a scenario of semantically interoperable data we can more readily employ machines to reason over complex knowledge, and support surveillance decision-making holistically. Data variety and even issues of data accessibility are resolved, rather than being barriers. In an ongoing project in Sweden, for example (**Figure 3**), we are researching methods to combine evidence from analysis, rather than combining data directly. Data are analyzed at source, with signals being compiled centrally.

Moreover, a data-driven surveillance framework assumes that decision-makers have access to the outputs of big data analysis with the same level of "FAIRness" —this requires the availability of decision supporting dashboards that allow end users to query through the data sources in consumable formats, and navigate through the outputs of analysis in transparent ways. Most importantly, it requires that the value extracted from the data is returned to all relevant stakeholders (**Figure 3**), creating a positive cycle of encouragement not only for data accessibility, but also for data quality.

CONCLUSION

Solving the technological barriers to extracting information from big data is only the first step toward a framework for evidence-based decision making. Data-driven support to surveillance in practice will depend on having access to the right data, employing the right methods, and making the outputs accessible and understandable to the right stakeholders. Participants in the workshop, as well as several papers reviewed (1, 14, 19, 47), highlighted that data-driven components could support traditional surveillance, but that the surveillance systems of the future will be a hybrid of traditional and data-driven methods. System design should focus on health surveillance goals and utility to the decision-makers. Information generation is data-driven, but system design should not be. Using novel data sources to complement those used traditionally will merge the best of both worlds—though gains in timeliness and predictive power will come at the cost of dealing with all of the complexity in these novel data sources (1).

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

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

FUNDING

FD was funded by the Swedish Research Council for Sustainable Development (FORMAS). Grant number 2017-00779.

ACKNOWLEDGMENTS

We thank the Uppsala Health Summit organization responsible for organizing the workshop documented in the methods, and all the participants for their contributions.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.633977/full#supplementary-material

REFERENCES

1. Simonsen L, Gog JR, Olson D, Viboud C. Infectious disease surveillance in the big data era: toward faster and locally relevant systems. *J Infect Dis.* (2016) 214 (Suppl. 4):S380–5. doi: 10.1093/infdis/jiw376
2. Leyens L, Reumann M, Malats N, Brand A. Use of big data for drug development and for public and personal health and care. *Genet Epidemiol.* (2017) 41:51–60. doi: 10.1002/gepi.22012
3. Pfeiffer DU, Stevens KB. Spatial and temporal epidemiological analysis in the Big Data era. *Prev Vet Med.* (2015) 122:213–20. doi: 10.1016/j.prevetmed.2015.05.012
4. Lee ECCEC, Asher JMMJM, Goldlust S, Kraemer JDJDD, Lawson ABABB, Bansal S. Mind the scales: harnessing spatial big data for infectious disease surveillance and inference. *J Infect Dis.* (2016) 214 (Suppl. 4):S409–13. doi: 10.1093/infdis/jiw344
5. Gogoshin G, Boerwinkle E, Rodin AS. New algorithm and software (BNOmics) for inferring and visualizing bayesian networks from heterogeneous big biological and genetic data. *J Comput Biol.* (2017) 24:340–56. doi: 10.1089/cmb.2016.0100
6. Kumar ATK, Asamoah D, Sharda R. *Can Social Media Support Public Health? Demonstrating disease surveillance using big data analytics*. Puerto Rico: Americas Conference on Information Systems, AMCIS (2015).
7. O'Shea J, O'shea J, O'Shea J. Digital disease detection: a systematic review of event-based internet biosurveillance systems. *Int J Med Inform.* (2017) 101:15–22. doi: 10.1016/j.ijmedinf.2017.01.019
8. Dórea FCFC, Sanchez J, Revie CWCW. Veterinary syndromic surveillance: current initiatives and potential for development. *Prev Vet Med.* (2011) 101:1–17. doi: 10.1016/j.prevetmed.2011.05.004
9. Mayo M. *Big Data: Main Developments in 2016 and Key Trends*. (2017). Available online at: http://www.kdnuggets.com/2016/12/big-data-main-developments-2016-key-trends-2017.html (accessed November 11, 2019).
10. "Uppsala Health Summit." *Tackling Infectious Disease Threats: Prevent, Detect, Respond with a One Health Approach.* In: Conclusions from Uppsala Health Summit 10–11 October (2017). Uppsala (2017). Available online at: https://www.uppsalahealthsummit.se/digitalAssets/547/c_547164-l_1-k_uppsala-health-summit-post-conference-report-2017.pdf
11. Iwashyna TJ, Liu V. What's so different about big data? A primer for clinicians trained to think epidemiologically. *Ann Am Thorac Soc.* (2014) 11:1130–5. doi: 10.1513/AnnalsATS.201405-185AS
12. Hoffman S, Podgurski A. Big bad data: law, public health, and biomedical databases. *J Law, Med Ethics.* (2013) 41(Suppl. 1):56–60. doi: 10.1111/jlme.12040
13. Asokan GV, Asokan V. Leveraging "big data" to enhance the effectiveness of "one health" in an era of health informatics. *J Epidemiol Glob Health.* (2015) 5:311–4. doi: 10.1016/j.jegh.2015.02.001
14. Salathé M, Bengtsson L, Bodnar TJ, Brewer DD, Brownstein JS, Buckee C, et al. Digital epidemiology. Bourne PE, editor. *PLoS Comput Biol.* (2012) 8:1–5. doi: 10.1371/journal.pcbi.1002616
15. Vayena E, Salathé M, Madoff LC, Brownstein JS. Ethical challenges of big data in public health. *PLoS Comput Biol.* (2015) 11:e1003904. doi: 10.1371/journal.pcbi.1003904
16. Toh S, Platt R. Is size the next big thing in epidemiology? *Epidemiology.* (2013) 24:349–51. doi: 10.1097/EDE.0b013e31828ac65e
17. Gates MC, Holmstrom LK, Biggers KE, Beckham TR. Integrating novel data streams to support biosurveillance in commercial livestock production systems in developed countries: challenges and opportunities. *Front Public Heal.* (2015) 3:74. doi: 10.3389/fpubh.2015.00074
18. VanderWaal K, Morrison RB, Neuhauser C, Vilalta C, Perez AM. Translating big data into smart data for veterinary epidemiology. *Front Vet Sci.* (2016) 4:110. doi: 10.3389/fvets.2017.00110
19. Marvin HJP, Janssen EM, Bouzembrak Y, Hendriksen PJM, Staats M. Big data in food safety: an overview. *Crit Rev Food Sci Nutr.* (2017) 57:2286–95. doi: 10.1080/10408398.2016.1257481
20. McCue ME, McCoy AM. The scope of big data in one medicine: unprecedented opportunities and challenges. *Front Vet Sci.* (2017) 4:1–23. doi: 10.3389/fvets.2017.00194
21. Stevens KB, Pfeiffer DU. Sources of spatial animal and human health data: casting the net wide to deal more effectively with increasingly complex disease problems. *Spat Spatiotemporal Epidemiol.* (2015) 13:15–29. doi: 10.1016/j.sste.2015.04.003
22. Nuti SV, Wayda B, Ranasinghe I, Wang S, Dreyer RP, Chen SI, et al. The use of google trends in health care research: a systematic review. *PLoS ONE.* (2014) 9:e109583. doi: 10.1371/journal.pone.0109583
23. Kamel Boulos MN, Resch B, Crowley DN, Breslin JG, Sohn G, Burtner R, et al. Crowdsourcing, citizen sensing and sensor web technologies for public and environmental health surveillance and crisis management: trends, OGC standards and application examples. *Int J Health Geogr.* (2011) 10:67. doi: 10.1186/1476-072X-10-67
24. Han BA, Drake JM. Future directions in analytics for infectious disease intelligence: toward an integrated warning system for emerging pathogens. *EMBO Rep.* (2016) 17:e201642534. doi: 10.15252/embr.201642534
25. Bansal S, Chowell G, Simonsen L, Vespignani A, Viboud C. Big data for infectious disease surveillance and modeling. *J Infect Dis.* (2016) 214:S375–9. doi: 10.1093/infdis/jiw400
26. Definition of Interoperability. *HIMSS Dictionary of Healthcare Information Technology Terms, Acronyms and Organizations.* 2nd ed. Chicago, IL: HIMSS (2010). p. 190.
27. Noy N. Semantic integration: a survey of ontology-based approaches. *SIGMOD Rec.* (2004) 33:65–70. doi: 10.1145/1041410.1041421
28. Noy NF, McGuinness DL. *Ontology Development 101: A Guide to Creating Your First Ontology. Stanford Knowledge Systems Laboratory.* (2001) Available online at: http://protege.stanford.edu/publications/ontology_development/ontology101.pdf
29. Dórea FC, Vial F, Hammar K, Lindberg A, Lambrix P, Blomqvist E, et al. Drivers for the development of an Animal Health Surveillance Ontology (AHSO). *Prev Vet Med.* (2019) 166:39–48. doi: 10.1016/j.prevetmed.2019.03.002
30. Khoury MJMJMJ, Ioannidis JPAJPA. Medicine. Big data meets public health. *Science.* (2014) 346:1054–5. doi: 10.1126/science.aaa2709
31. Centers for Disease Control and Prevention (CDC). Syndromic surveillance. Reports from a national conference. *Morb Mortal Wkly Rep.* (2004) 53 (Suppl.):1–264.
32. Dórea FC, Vial F. Animal health syndromic surveillance: a systematic literature review of the progress in the last 5 years (2011–2016). *Vet Med Rep.* (2016) 7:157–69. doi: 10.2147/VMRR.S90182
33. Dupuy C, Bronner A, Watson E, Wuyckhuise-Sjouke L, Reist M, Fouillet A, et al. Inventory of veterinary syndromic surveillance initiatives in Europe (Triple-S project): current situation and perspectives. *Prev Vet Med.* (2013) 111:220–9. doi: 10.1016/j.prevetmed.2013.06.005
34. Smith GE, Elliot AJ, Lake I, Edeghere O, Morbey R, Catchpole M, et al. Syndromic surveillance: Two decades experience of sustainable systems—Its people not just data! Epidemiol Infect. (2019) 147:e101. doi: 10.1017/S0950268819000074
35. Huang T, Lan L, Fang X, An P, Min J, Wang F. Promises and challenges of big data computing in health sciences. *Big Data Res.* (2015) 2:2–11. doi: 10.1016/j.bdr.2015.02.002
36. Wang W, Krishnan E. Big data and clinicians: a review on the state of the science. *JMIR Med Inform.* (2014) 2:e1. doi: 10.2196/medinform.2913
37. Ouyang Z, Sargeant J, Thomas A, Wycherley K, Ma R, Esmaeilbeigi R, et al. A scoping review of "big data", "informatics", and "bioinformatics" in the animal health and veterinary medical literature. *Anim Heal Res Rev.* (2019) 1–18. doi: 10.1017/S1466252319000136
38. Buckee C. Improving epidemic surveillance and response: big data is dead, long live big data. *Lancet Digit Heal.* (2020) 2:e218–20. doi: 10.1016/S2589-7500(20)30059-5
39. Chiolero A, Chiolero A, Chiolero A, Chiolero A, Buckeridge D. Glossary for public health surveillance in the age of data science. *J Epidemiol Community Health.* (2020) 74:612–6. doi: 10.1136/jech-2018-211654

40. Brownson RC, Samet JM, Bensyl DM. Applied epidemiology and public health: are we training the future generations appropriately? *Ann Epidemiol.* (2017) 27. doi: 10.1016/j.annepidem.2016.12.002
41. RISKSUR surveillance design framework. Available online at: https://survtools.org/wiki/surveillance-design-framework/ (accessed November 11, 2020).
42. Dammann O. Data, information, evidence, and knowledge: a proposal for health informatics and data science. *Online J Public Health Inform.* (2019) 10:e224. doi: 10.5210/ojphi.v10i3.9631
43. Dolley S. Big data's role in precision public health. *Front Public Heal.* (2018) 6:681. doi: 10.3389/fpubh.2018.00068
44. Althouse BM, Scarpino S V., Meyers LA, Ayers JW, Bargsten M, Baumbach J, et al. Enhancing disease surveillance with novel data streams: challenges and opportunities. *EPJ Data Sci.* (2015) 4:1–8. doi: 10.1140/epjds/s13688-015-0054-0
45. Antoine-Moussiaux N, Vandenberg O, Kozlakidis Z, Aenishaenslin C, Peyre M, Roche M, et al. Valuing health surveillance as an information system: interdisciplinary insights. *Front Public Heal.* (2019) 7:138. doi: 10.3389/fpubh.2019.00138
46. Wilkinson MD, Dumontier M, Aalbersberg IjJ, Appleton G, Axton M, Baak A, et al. The FAIR Guiding Principles for scientific data management and stewardship. *Sci Data.* (2016) 3:160018. doi: 10.1038/sdata.2016.18
47. Kostkova P. *A Roadmap to Integrated Digital Public Health Surveillance: The Vision and the Challenges*. In: *Companion - Proceedings of the 22nd International Conference on World Wide Web.* Rio de Janeiro (2013). doi: 10.1145/2487788.2488024

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.

The reviewers JA and JB declare a past co-authorship with one of the authors FD and state that the process nevertheless met the standards of a fair and objective review.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 12 April 2021
doi: 10.3389/fvets.2021.646672

An Empirical Analysis on the Longevity of Dairy Cows in Relation to Economic Herd Performance

*Imke Vredenberg[1], Ruozhu Han[2], Monique Mourits[2], Henk Hogeveen[2] and Wilma Steeneveld[1]**

[1] Department of Population Health Sciences, Faculty of Veterinary Medicine, Utrecht University, Utrecht, Netherlands,
[2] Business Economics Group, Wageningen University, Wageningen, Netherlands

Several studies have stated the various effects of an increased dairy cow longevity on economic herd performance, but empirical studies are lacking. This study aimed to investigate the association between longevity of dairy cows and the economic performance of dairy herds based on longitudinal Dutch accounting data. Herd and farm accounting data ($n = 855$ herds) over the years 2007–2016 were analyzed. Herd data contained yearly averages on longevity features, herd size and several production variables. Longevity was defined as the age of cows at culling and by lifetime milk production of culled cows. Farm accounting data contained yearly averages on revenues, fixed and variable costs of the herds, by which gross margins were defined. Data was analyzed using generalized linear mixed modeling, with gross margin as dependent variable. The independent variables consisted of average age of culled cows, average lifetime production of culled cows, year, herd size, herd intensity (milk production per ha), herd expansion rate, soil type, milking system, successor availability, total full-time equivalent, heifer ratio (% of heifers per cow) and use of outsourced heifer rearing. Herd was included as a random effect to account for the heterogeneity among herds. Descriptive statistics showed that the average age of culled cows was 5.87 (STD = 0.78) years and the average lifetime milk production of culled cows was 31.87 (STD = 7.56) tons per cow with an average herd size of 89 cows (STD = 38.85). The average age of culled cows was stable over the 10 years (variation between 5.79 AND 5.90 years). The gross margin was on average €24.80/100 kg milk (STD = 4.67), with the lowest value in year 2009 and the highest value in year 2013. Gross margin was not significantly associated with age of culled cows and lifetime milk production of culled cows. Variance in longevity between herds was large (STD = 0.78 years) but herds with a higher longevity did not perform economically better nor worse than herds resulting in lower longevity. This indicates that, within current practice, there is potential for improving longevity in order to meet society's concerns on animal welfare and environmental pollution, without affecting the economic performance of the herd.

Keywords: dairy (cows), economics, longevity, culling age, lifetime milk production, accounting data

Edited by:
*Bouda Vosough Ahmadi,
European Commission for the Control of Foot and Mouth Disease (EuFMD), Italy*

Reviewed by:
*Beat Thomann,
University of Bern, Switzerland
Georgina Limon,
Pirbright Institute, United Kingdom*

***Correspondence:**
*Wilma Steeneveld
w.steeneveld@uu.nl*

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: *27 December 2020*
Accepted: *17 March 2021*
Published: *12 April 2021*

Citation:
Vredenberg I, Han R, Mourits M, Hogeveen H and Steeneveld W (2021) An Empirical Analysis on the Longevity of Dairy Cows in Relation to Economic Herd Performance. Front. Vet. Sci. 8:646672. doi: 10.3389/fvets.2021.646672

INTRODUCTION

Longevity of a dairy cow can be defined as the total lifespan of a cow or as the length of productive life (1). The productive lifespan of average dairy cows in industrialized countries varies from <3 years (2) to at least 4.5 year (3). These cows calve for the first time at ∼2 years of age, which brings their total lifespan from birth to departure from the herd between 4.5 and 6.5 years. The average total lifespan of dairy cows in the Netherlands in 2018 was 5.5 years (4), while the natural lifespan of dairy cattle is ∼20 years (5). Hence, cows are culled well before the end of their natural lifespan, which is common for animals in dairy livestock production. The decision to cull a cow is primarily driven by economic considerations as made by the farmer. Therefore, dairy replacement management decisions largely determine the average productive lifespan of dairy cattle (6). Decisions to cull and replace a dairy cow are driven by the cow's level of production, reproduction and health in comparison to the other cows in the herd and the available replacement animals. In the Netherlands, the main culling reasons in 2011 were poor fertility, mastitis and claw disorders (7).

When cows have a prolonged longevity less replacement is needed, and therefore total rearing costs will be lower and rearing costs are spread out over a longer productive life. In the Netherlands, rearing costs of a heifer are on average between €1,423 and 1,715 per heifer (8), reflecting one of the highest dairy production costs. Moreover, a higher longevity will result in more cows in higher parities, and thus in a higher proportion of cows in higher producing age groups, and thus a higher average milk production of the herd. Under milk quota circumstances a higher herd production does have little value, but the farmer then has the option to reduce the herd size due to a higher milk production per cow. A higher longevity might, however, also result in disadvantages, such as increased health and reproduction problems and a reduction in genetic improvement (9).

Besides economic consequences, an increase in longevity will also have environmental and social consequences. Cows with an increased longevity produce less methane per kg of milk (10), improve environmental sustainability (11) and indicate good animal welfare on the farm (12). Impacts on the environment and animal welfare have become increasingly important in public debate.

As stated in several studies [e.g., (1, 13)] a higher longevity can result in less rearing costs and increased returns from a higher lifetime milk production. Empirical studies that support these expectations are, however, lacking. So, it is not yet known from practice, whether farms with a higher longevity perform economically better than farms with a lower longevity of the cows.

The aim of this research is to investigate the association between longevity of dairy cows and the economic performance of dairy herds based on available Dutch accounting data.

MATERIALS AND METHODS

Data

Anonymized yearly herd level data was obtained from a Dutch accounting agency (Flynth, Arnhem, the Netherlands). The data represented 2,809 herds with 30,170 yearly records from 2007–2016. The accounting dataset contained information on economic performance indicated by revenues (e.g., milk revenues) and fixed and variable costs (e.g., feed costs and veterinary costs), as well as on general herd characteristics (e.g., soil type, number of full-time employees). Economic data was expressed in absolute values and in ratios per 100 kg milk produced per year.

The annual farm accountancy data of these 2,809 herds were subsequently merged with herd performance data derived from the Cattle Improvement Cooperative (CRV, Arnhem, the Netherlands). These data included herd information on herd size, longevity features (e.g., age of the cows in days and number of production days of the cows) and production, such as 305-day milk production and 305-day percentage fat and protein. For 2,105 herds CRV herd performance data was available.

Data Management

Only data from commercial dairy herds were selected for further analysis. A commercial Dutch dairy farm was defined as a herd with more than 30 cows and an average 305-day milk production above 4,000 kg per cow. It was argued that the amount of labor needed to manage at least 30 cows indicates a commercial way of farming. Moreover, by using 30 cows, non-commercial farms like hobby herds and petting farms were excluded. Furthermore, herds with missing values on important variables (e.g., 305-day milk production, age at culling, lifetime milk production of culled cows and number of heifers) were removed (**Figure 1**). Subsequently, organic herds ($n = 22$ herds) and a herd with an unexplainable high milk revenue ($n = 1$ herd) were excluded, because on all these herds milk revenues were distinct higher than on conventional herds. Also, herds producing dairy products (e.g., cheese, yogurt) ($n = 30$ herds), with non-dairy revenues higher than €1.00/100 kg milk ($n = 68$ herds) or with an extreme heifer ratio (≤ 0.08; ≥ 0.5) ($n = 12$ herds) were excluded. Heifer ratio was calculated by the number of heifers that have calved divided by the average number of milking cows annually. It was argued that these herds may had other business activities than only dairy production, like cow trading, crop production, or running a farm shop. Since the longevity performance of herds can be better analyzed based on data of several years only farms with continuous data of 10 years were selected. As a consequence, farms that quitted farming or changed accounting agency during the evaluated period were excluded from further analysis. The final balanced dataset contained information on 855 commercial dairy herds with 10 years of consecutive observations (**Figure 1**).

The average age and lifetime milk production of culled cows were chosen to reflect the longevity features of the herd. Other selected variables in the data were selected based on an expected association with gross margin. The selected variables were herd size, use of outsourced young stock rearing (yes/no), number

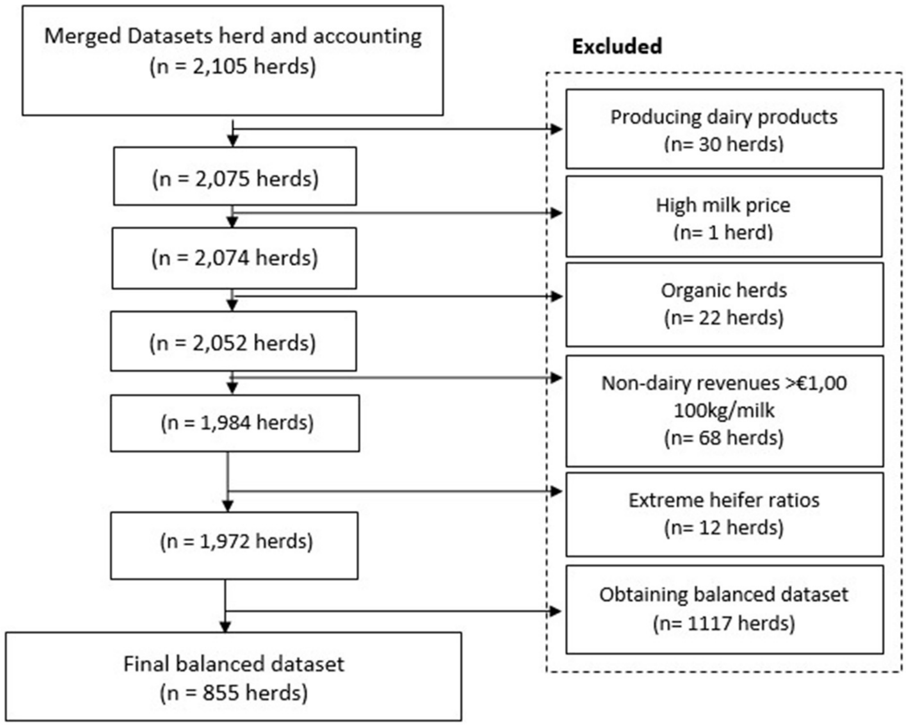


FIGURE 1 | Data editing steps, starting with the merged dataset till the final dataset containing 855 herds.

of full-time employees, land area, whether the farmer has a successor (yes/no), soil type (sand vs. non-sand), milking system (conventional vs. automatic milking system), total herd milk production and number of cows per ha. Soil type was selected as Dutch farms producing on different soil types (especially clay vs. sand) differ in milk revenues and costs for purchasing feed (14). The variable having a successor was selected as it was expected that farmers with a successor make different management decisions than those without a successor, hence, resulting in different gross margins. In addition, the variables herd expansion, production intensity and heifer ratio were calculated. Herd expansion reflected the ratio of herd size changes on the basis of reference year 2007. Production intensity indicated the annual average milk production in tons per hectare. To analyse the economic performance of herds, the gross margin for dairy production was calculated as the total revenues minus the total variable costs and was expressed in euros per 100 kg milk produced (**Figure 2**).

Data Analysis

The linearity of the relationships between the selected variables and gross margin were visually inspected by creating boxplots. In order to avoid multicollinearity, a Pearson correlation coefficient above 0.6 between continuous independent variables was used to remove the strongly correlated variables. Consequently, the total ha of the farm (highly correlated with herd size) and the average number of cows per ha (highly correlated with average tons of milk production per ha) were removed from further analysis. Two generalized linear mixed models (GLMM) were developed to analyse the association of dairy cow longevity (measured either by age or by lifetime milk production of culled cow) with economic performance of herds. The dependent variable of these models was the gross margin of the herd, reflecting the economic performance. The independent variables consisted of age or lifetime milk production of culled cows (hence 2 models) in combination with the independent variables soil type, milking system, whether a successor was available, whether young stock was outsourced, number of full-time employee, heifer ratio, herd expansion, herd size and herd intensity. A year variable was forced into both models to account for potential year effects (e.g., milk price changes). Moreover, to capture the unobserved herd related heterogeneity, such as management strategy, a herd variable was entered into the models as a random effect. To account for the covariance among the consecutive gross margin measurements within herds, competing covariance structures (i.e., independent, compound symmetry, first-order autoregressive, first-order autoregressive moving average and unstructured) were tested for their fit. Based on the Akaike information criterion, the unstructured covariance structure resulted in the best model fit and was eventually used in the presented models.

RESULTS

Descriptive Statistics

Over the evaluated period of 2007 to 2016, the average age of culled cows was equal to 5.87 years. Meanwhile, the average lifetime milk production of culled cows was 31.87 tons per cow.

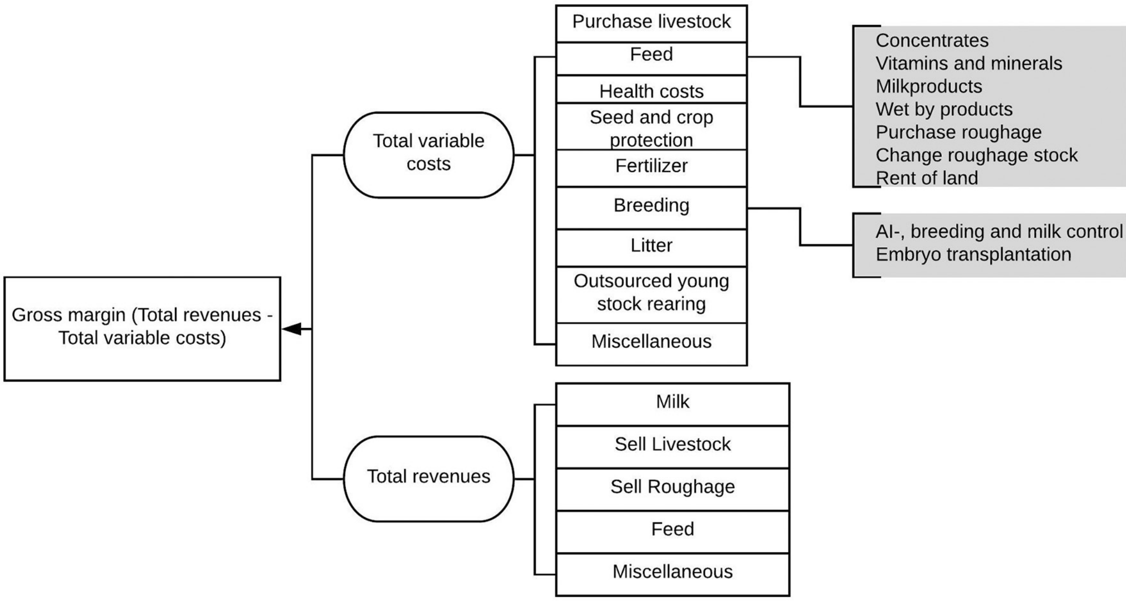


FIGURE 2 | Overview of revenues and costs accounted for in the gross margin of the herds for dairy production. Examples of miscellaneous costs are costs related to water, electricity and manure disposal. Examples of miscellaneous revenues are subsidies and rental of barn space. Feed revenues include, for instance, the sales of silage.

TABLE 1 | Descriptive statistics on continuous variables over herds and years (*n* = 855 herds).

	Description (unit)	Mean	STD	5% percentile	95% percentile
Age culled cows	Age of culled cows (years)	5.87	0.78	4.75	7.24
Lifetime milk production	Lifetime milk production of culled cows (tons)	31.87	7.56	20.73	45.16
Total FTE	Total number of full-time employees	1.88	0.72	1	3
Heifer ratio	Number of calved heifers per average cow present in the herd	0.24	0.06	0.15	0.33
Herd size	Number of cows present in the herd	88.87	38.85	44	161
Herd expansion	Herd size change from 2007 to 2016 in relation to base year 2007	1.15	0.23	0.92	1.57
Herd intensity	Milk production per ha (tons)	15.84	4.46	9.97	23.63

The standard deviations (STD) of the longevity variables between farms, were larger than the average STD within farms. The STD of age of culled cows between farms was 0.78 years, while the average STD within farms was equal to 0.59 years. For the lifetime milk production, the STD between farms was 7.56 tons, while the average STD within farms was 5.37 tons. The average herd size over the evaluated period was almost 89 cows (**Table 1**) and increased from, on average, 76 cows in 2007 to, on average, 103 cows in 2016.

Average total variable costs were €14.54/100 kg milk, while the average total revenues equalled €39.34/100 kg milk. The average gross margin over the evaluated period was €24.8/100 kg milk (**Table 2**).

The descriptive statistics on age of culled cows, lifetime milk production of culled cows, and gross margin for different categories of the categorical variables year, soil type, milking system, having a successor and making use of outsourced youngstock rearing are presented in **Table 3**. The average age of culled cows was rather constant over the years (variation between 5.79 and 5.90 years). A slight increase in average lifetime milk production of culled cows was displayed throughout the evaluated period (30.82–32.65 tons). Among the categorical variables, such as soil type, milking system, whether having a successor and whether young stock rearing was outsourced, there were almost no differences in average age of culled cows and average lifetime milk production of culled cows. The average gross margin varied substantial between years, with the lowest value realized in 2009 (€18.48/100 kg milk), and the highest value in 2013 (€29.90/100 kg milk). The average gross margin tended to be higher in farms with sandy soil and farms with a conventional milking system, compared to farms with non-sandy soil and an automatic milking system, respectively. In addition, herds outsourcing their young stock rearing had a lower average gross margin (€22.92/100 kg milk) than herds not outsourcing young stock rearing (€25.02/100 kg milk).

Regression Analysis

Table 4 presents the results of the developed GLMM to study the association between longevity (age of culled cows and lifetime milk production of culled cows) and economic herd performance (gross margin). Overall, the results did not demonstrate any significant association between the longevity variables and gross margin. Of the evaluated independent variables soil type, milking system, use of outsourced heifer rearing, heifer ratio and herd intensity were significantly associated with gross margin. The strength of these associations was comparable among the two models. The use of outsourced youngstock rearing was associated with on average a €1.02/100 kg milk lower gross margins compared to the use of only own youngstock rearing. In addition, herds on sandy soils were associated with a €0.56/100 kg milk higher gross margins than herds on non-sandy soils, while the use of an automatic milking system was associated with €0.52/100 kg milk lower gross margins than on farms with a conventional milking system. One ton of milk production increase per ha was associated with an decrease in gross margin by €0.13/100 kg milk. An increase in heifer ratio of 0.1 (hence, having 10% more calved heifers in relation to milking cows) was associated with an increase in gross margin by €0.08/100 kg milk.

The marginal R^2 (variance explained by fixed effects) and the conditional R^2 (variance explained by entire model) of the model on age of culled cows were 0.60 and 0.80, respectively. The same values were found for the model on lifetime milk production of culled cows.

TABLE 2 | Descriptive statistics on variable costs, revenues and gross margin (in €/100 kg milk) over herds and years ($n = 855$ herds).

		Mean	STD
Variable costs	Feed	8.95	2.43
	Purchase livestock	0.47	1.47
	Fertilizer	1.04	0.37
	Seed and crop protection	0.56	0.30
	Health	0.98	0.41
	Breeding	0.95	0.31
	Outsourced young stock rearing	0.17	0.67
	Litter	0.46	0.35
	Miscellaneous[a]	0.96	0.38
	Total	14.54	1.99
Revenues	Milk	36.24	4.70
	Sell livestock	2.96	1.65
	Sell roughage	0.13	0.43
	Feed[b]	0.0001	0.01
	Miscellaneous[c]	0.01	0.05
	Total	39.34	5.15
Gross margin	Total revenues – total variable costs	24.80	4.67

[a] *e.g., water, electricity and manure disposal.*
[b] *Selling of silage.*
[c] *e.g., subsidies and rental of barn space.*

DISCUSSION

The average age of culled cows was rather constant over the evaluated period (variation between 5.79 and 5.90 years). Corresponding averaged STD of 0.78 years, however, indicated

TABLE 3 | The number of observations, mean and standard deviation (STD) of average longevity variables (age and lifetime milk production of culled cows) and gross margin per categorical variable.

			Age of culled cows (year)		Lifetime milk production of culled cows (tons)		Gross margin (€/100 kg milk)	
		***N* obs**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**
Year[a]	2007		5.87	0.84	30.82	7.72	26.58	2.56
	2008		5.94	0.83	31.74	7.80	25.13	3.06
	2009		5.89	0.76	31.59	7.11	18.48	2.65
	2010		5.86	0.75	31.74	7.49	25.20	2.59
	2011		5.79	0.77	31.43	7.68	28.00	2.87
	2012		5.78	0.73	31.60	7.39	24.98	2.96
	2013		5.90	0.84	32.48	7.97	29.29	3.14
	2014		5.89	0.74	32.45	7.32	29.09	3.38
	2015		5.86	0.78	32.24	7.55	21.28	3.47
	2016		5.89	0.73	32.65	7.32	20.01	3.26
Soil type	Sandy soil	6,067	5.86	0.79	31.77	7.51	24.95	4.67
	Other soil	2,483	5.88	0.76	32.14	7.65	24.44	4.64
Milking system	Conventional	7,023	5.89	0.79	31.91	7.70	24.90	4.61
	Automatic	1,527	5.74	0.70	31.71	6.88	24.37	4.92
Successor	No	5,410	5.87	0.79	31.66	7.43	24.84	4.69
	Yes	3,140	5.85	0.77	32.24	7.75	24.74	4.64
Outsourcing young stock rearing	No	7,674	5.86	0.78	31.73	7.56	25.02	4.62
	Yes	876	5.90	0.75	33.16	7.44	22.92	4.67

[a] *In comparison to the other categorical variables, each year category consists of only one herd measurement.*

TABLE 4 | Results of the generalized linear mixed models on association between longevity (age of culled cows and lifetime milk production of culled cows) and gross margin (in €/100 kg milk).

		Age of culled cows		Lifetime milk production of culled cows	
		Estimate	***P*-value**	**Estimate**	***P*-value**
Intercept		28.690	< 0.0001	28.770	< 0.0001
Year	2007	Ref.[a]		Ref.[a]	
	2008	−1.356	< 0.0001	−1.352	< 0.0001
	2009	−7.959	< 0.0001	−7.955	< 0.0001
	2010	−1.196	< 0.0001	−1.190	< 0.0001
	2011	1.640	< 0.0001	1.645	< 0.0001
	2012	−1.386	< 0.0001	−1.380	< 0.0001
	2013	3.044	< 0.0001	3.054	< 0.0001
	2014	2.881	< 0.0001	2.891	< 0.0001
	2015	−4.825	< 0.0001	−4.816	< 0.0001
	2016	−5.989	< 0.0001	−5.978	< 0.0001
Age culled cows (years)		−0.017	0.5920		
Lifetime milk production (tons)				−0.006	0.0915
Soil type	Sandy soil	Ref.[a]		Ref.[a]	
	Other soil	−0.564	0.0004	−0.561	0.0004
Milking system	Conventional	Ref.[a]		Ref.[a]	
	Automatic	−0.519	< 0.0001	−0.518	< 0.0001
Successor	No	Ref.[a]		Ref.[a]	
	Yes	−0.070	0.4165	−0.068	0.4302
Outsourcing young stock rearing	No	Ref.[a]		Ref.[a]	
	Yes	−1.023	< 0.0001	−1.020	< 0.0001
Total full-time employee		−0.025	0.6860	−0.024	0.7064
Heifer ratio		0.823	0.0241	0.805	0.0273
Herd expansion		−0.041	0.8614	−0.040	0.8631
Herd size		0.001	0.7666	0.001	0.7997
Herd intensity (tons milk/ha)		−0.129	< 0.0001	−0.128	< 0.0001

[a] *This category is used as reference category in the regression analysis.*

distinct differences in culling age between herds. Similarly, averaged observed variance in lifetime milk production (STD 7.56 tons) indicated relevant differences between herds, while the average annual lifetime milk production of culled cows only slightly varied around a value of 31.9 tons of milk. Hence on herd population level, longevity did not alter much during the evaluated years 2007–2016. The gross margin was on average €24.80/100 kg milk (STD = 4.67). It might be possible that a very small proportion of this gross margin was due to non-dairy production. This will, however, be a neglectable small proportion as dairy herds with distinct other business activities were excluded.

Modeling results indicated that longevity (age and lifetime milk production of culled cows) was not significantly associated with the gross margin of commercial Dutch dairy herds. Herds with higher longevity did not have a significantly higher nor lower gross margin than herds with a lower longevity. Although it is frequently reported that a higher longevity will have positive economic consequences because of less young stock rearing and a higher average milk production [e.g., (1, 13)], this was not observed in the observational data used in the current study. Negative effects of a higher longevity, like the reduction in livestock sales due to a reduction in the removal of dairy cows or increased health and/or reproduction costs (15, 16), might have leveled out potential positive consequences. Moreover, this balance between positive and negative effects between years might have been influenced by differences in price levels as well as by management changes triggered by policy alterations (e.g., abolishment milk quota). The effects of longevity on specific costs or revenues (e.g., health costs, livestock sales) can be investigated in the future.

The independent variable year was strongly associated with the gross margin, which was largely caused by the differences in milk price between the years. Since the milk price in the Netherlands was lowest in 2009 and highest in 2013 (respectively, €27.51/100 kg milk and €43.04/100 kg milk) (17), it was to be expected that the year 2009 was associated with the lowest gross margin, and the year 2013 with the highest gross margin (**Table 3**). Moreover, the years 2013–2015 (period in which farmers already anticipated on the abolishment of the milk quota system in 2015) can be considered as years where farmers might have made different strategic management decisions (e.g., building new barns, rearing more or less youngstock, and culling more or less cows) than in the more stable (quota restricted) years before that period, resulting in some year specific influences. To account for any specific effects between longevity and year that might have affected the gross margin, interaction terms have been tested but these turned out to be insignificant (data not shown).

It remains, however, inherent to field data that results are influenced by external changes, such as national agricultural policies and changes in price levels. Moreover, the gross margin is only a partial measure of farm profitability. Farm assets such as the modernity of the farm buildings and farm machinery, the quality and amount of land and the amount of own labor. Hence, the fixed costs are not taken into account. It is difficult to work with economic measures such as net profit because in accountancy data, the value of these assets is not well-known. In the future, other methods, such as the use of an efficiency analysis (18, 19), where the farm's relative efficiency in terms of producing milk given a certain amount of resources is evaluated may provide a more complete economic view of the association between cow longevity and farm performance. On the other hand, because most of the fixed costs are linked to farm structure which cannot be changed in the short run, gross margin does provide a good indication of the short term profitability of a farm.

The independent variables milking system, use of outsourced heifer rearing, herd intensity, soil type and heifer ratio were not significantly associated with the gross margin (**Table 4**). Herds with an automatic milking system had on average a lower economic performance than herds with a conventional milking system, which was an expected association based on earlier findings of Bijl et al. (20) and Steeneveld et al. (19). Making use of outsourced young stock rearing was also associated with a lower gross margin than the use of own young stock rearing. This was expected as outsourced young stock rearing means that all costs (feed, housing and labor) are represented as a variable costs in the gross margin. While with own young stock rearing, only the feed costs [approximately one-third of the total costs of young stock rearing; (8)] are represented in the variable costs and housing and labor are fixed costs. More intensive farms (defined as more kg milk per hectare) were associated with a lower gross margin, most probably due to higher purchasing feed costs than less intensive farms. Also farms on non-sandy soil were associated with a lower gross margin due to lower milk revenues than on sandy soil (data not shown). Heifer ratio was positively associated with gross margin, indicating that farms that had more calved heifers per milking cow had a higher gross margin in comparison with farms that have less calved heifers per milking cow. This was to some extent an unexpected association as generally the amount of young stock is reflected in the heifer ratio. A higher heifer ratio, hence more young stock, would, in theory, lead to more variable costs and hence a lower gross margin. This assumption is, however, only valid in a stable farm production system, which was not the case during the evaluated period. Triggered by the abolishment of the milk quota in 2015, farmers already anticipated in the preceding years 2013–2014 by increasing their young stock rearing resulting in higher rearing costs, while the revenues resulting from this accelerated heifer rearing were not obtained until 2 years later. Due to this rearing time lag the increase in youngstock rearing was not direct captured by the heifer ratio. Hence, increased rearing costs were related to unaltered heifer ratios, while the additional revenues as a result of the increased rearing were related to higher ratios.

Longevity of dairy cows has been mostly evaluated in terms of culling of individual cows, as longevity is determined by the moment of the cows' departure from the herd for voluntary or involuntary reasons. Culling reasons and risk factors for culling are intensively studied worldwide [e.g., (21–23)]. Also studies on optimization of culling decisions and costs of culling (24–26) are performed. Empirical analysis on the economic consequences of a higher longevity or a lower culling rate are however lacking. Only De Vries (6) and De Vries and Mercondes (13) discussed the economic consequences of a higher longevity at the herd level and stressed lower replacement costs and a higher lifetime milk production. It was, however, also mentioned that a higher longevity is not necessarily profitable per cow per year, since the facilities are the most limiting factor (13). Our study is the first study that analyzed the economic consequences of longevity in an empirical way, and the Dutch commercial farm economics was taken into account by using farm accounting data. The gross margin was expressed per 100 kg milk per year as under Dutch milk quota circumstances (until 2015) kg of milk was the most limiting factor.

De Vries and Mercondes (13) argued that it is conceivable that society will start to demand a higher longevity that is more in line with the natural life expectancy, given that health problems are major drivers of culling at a young age. According to the (27) an increase in longevity of 2 years would be desirable. However, forcefully increasing longevity to such an extent, without adjustments on health management will, however, have negative effects, such as increasing incidences of diseases. Therefore, additional costs for changes in health management and housing (access to pasture, improving cow comfort) will be needed to improve longevity in a structural way (13). Although observational studies, due to a lack of experimental control, have disadvantages in interpretation, the data in this study may help the dairy sector in their decisions regarding in setting their ambitions regarding longevity.

In conclusion, longevity (age at culling, lifetime milk production of culled cows) was not statistical significantly associated with the gross margin of Dutch dairy herds, based on observational longevity and accounting data. Variance in longevity between herds was large but results demonstrated that herds with a higher longevity did not perform economically better nor worse than herds resulting in lower longevity. This indicates that within current practice there is potential for improving longevity in order to meet society's concerns on animal welfare and environmental pollution without affecting the economic performance of the herd.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

IV and RH: data analysis and drafting the manuscript. MM and WS: drafting the manuscript and critical revision of the article. HH: critical revision of the article. All authors contributed to the article and approved the submitted version.

FUNDING

RH and availability of the data are financially supported by the Sino-Dutch Dairy Development Center.

ACKNOWLEDGMENTS

The authors thank Dr. Bart van den Borne (chair group Business Economics, Wageningen University, Wageningen, the Netherlands) for help with the statistical modeling. The authors also thank CRV and Flynth for providing the data.

REFERENCES

1. Schuster JC, Barkema HW, De Vries A, Kelton DF, Orsel K. Invited review: Academic and applied approach to evaluating longevity in dairy cows. *J Dairy Sci.* (2020) 103:11008–24. doi: 10.3168/jds.2020-19043
2. Pinedo PJ, Daniels A, Shumaker J, De Vries A. Dynamics of culling for Jersey, Holstein, and Jersey × Holstein crossbred cows in large multibreed dairy herds. *J Dairy Sci.* (2014) 97:2886–95. doi: 10.3168/jds.2013-7685
3. Kerslake JI, Amer PR, O'Neill PL, Wong SL, Roche JR, Phyn CVC. Economic costs of recorded reasons for cow mortality and culling in a pasture-based dairy industry. *J Dairy Sci.* (2018) 101:1795–803. doi: 10.3168/jds.2017-13124
4. CRV. *Bedrijven en Koeien in Cijfers*. (2019). Retrieved from: https://www.cooperatie-crv.nl/downloads/stamboek/bedrijven-en-koeien-in-cijfers/ (accessed December 1, 2020).
5. Nowak RM, Walker EP. *Walker's Mammals of the World*. Vol. 1. Baltimore, MD: JHU Press (1999).
6. De Vries A. Symposium review: why revisit dairy cattle productive lifespan? *J Dairy Sci.* (2020) 103:3838–45. doi: 10.3168/jds.2019-17361
7. Zijlstra J, Boer M, Buiting J, Colombijn-Van der Wende K, Andringa EA. *Routekaart Levensduur (668)*. (2013). Retrieved from: https://edepot.wur.nl/275131 (accessed December 1, 2020).
8. Mohd Nor N, Steeneveld W, Mourits MC, Hogeveen H. Estimating the costs of rearing young dairy cattle in the Netherlands using a simulation model that accounts for uncertainty related to diseases. *Prev Vet Med.* (2012) 106:214–24. doi: 10.1016/j.prevetmed.2012.03.004
9. De Vries A. Economic trade-offs between genetic improvement and longevity in dairy cattle. *J Dairy Sci.* (2017) 100:4184–92. doi: 10.3168/jds.2016-11847
10. Grandl F, Furger M, Kreuzer M, Zehetmeier M. Impact of longevity on greenhouse gas emissions and profitability of individual dairy cows analysed with different system boundaries. *Animal.* (2018) 13:198–208. doi: 10.1017/S175173111800112X
11. Overton MW, Dhuyvetter KC. Symposium review: An abundance of replacement heifers: what is the economic impact of raising more than are needed? *J Dairy Sci.* (2020) 103:3828–37. doi: 10.3168/jds.2019-17143
12. Barkema HW, von Keyserlingk MAG, Kastelic JP, Lam TJGM, Luby C, Roy J-P, et al. Invited review: changes in the dairy industry affecting dairy cattle health and welfare. *J Dairy Sci.* (2015) 98:7426–45. doi: 10.3168/jds.2015-9377
13. De Vries A, Marcondes MI. Review: overview of factors affecting productive lifespan of dairy cows. *Animal.* (2020) 14:s155–64. doi: 10.1017/S1751731119003264
14. Evers AG, de Haan D, Van den Pol-Van Dasselaar A, Philipsen AP. Weiden onder moeilijke omstandigheden: een studie naar inkomensverschillen tussen weiden en opstallen. In: *Dutch, Summary in English*. Wageningen: Wageningen UR; Animal Sciences Group (2008). Retrieved from: https://edepot.wur.nl/37812 (accessed February 20, 2021).
15. Beaudeau F, Seegers H, Ducrocq V, Fourichon C, Bareille N. Effect of health disorders on culling in dairy cows: a review and a critical discussion. *Ann Zootech.* (2000) 49:293–311. doi: 10.1051/animres:2000102
16. Mohd Nor N, Steeneveld W, Hogeveen H. The average culling rate of Dutch dairy herds over the years 2007 to 2010 and its association with herd reproduction, performance and health. *J Dairy Res.* (2013) 81:1–8. doi: 10.1017/S0022029913000460
17. Wageningen University and Research. *Agrarische Prijzen. Agrimatie*. (2020). Retrieved from: https://www.agrimatie.nl/Prijzen.aspx?ID=15125 (accessed December 1, 2020).
18. Oude Lansink A, Pietola K, Bäckman S. Efficiency and productivity of conventional and organic farms in Finland 1994-1997. *Eur Rev Agr Econ.* (2002) 29:51–65. doi: 10.1093/erae/29.1.51
19. Steeneveld W, Tauer LW, Hogeveen H, Oude Lansink A. Comparing technical efficiency of farms with an automatic milking system and a conventional milking system. *J Dairy Sci.* (2012) 95:7391–8. doi: 10.3168/jds.2012-5482
20. Bijl R, Kooistra SR, Hogeveen H. The profitability of automatic milking on Dutch dairy farms. *J Dairy Sci.* (2007) 90:239–48. doi: 10.3168/jds.S0022-0302(07)72625-5
21. Gröhn Y, González R, Wilson DJ, Hertl J, Bennett G, Schulte H, et al. Effect of pathogen-specific clinical mastitis on herd life in two New York State dairy herds. *Prev Vet Med.* (2005) 71:105–25. doi: 10.1016/j.prevetmed.2005.06.002
22. Sewalem A, Miglior F, Kistemaker G, Sullivan PV, Van Doormaal B. Relationship between reproduction traits and functional longevity in Canadian dairy cattle. *J Dairy Sci.* (2008) 91:1660–8. doi: 10.3168/jds.2007-0178
23. Rilanto T, Reimus K, Orro T, Emanuelson U, Viltrop A, Mõtus K. Culling reasons and risk factors in Estonian dairy cows. *BMC Vet Res.* (2020) 16:1–16. doi: 10.1186/s12917-020-02384-6
24. Kristensen AR. Optimal replacement and ranking of dairy cows under milk quotas. *Acta Agric Scand.* (1989) 39:311–8. doi: 10.1080/00015128909438523
25. Demeter RM, Kristensen AR, Dijkstra J, Lansink AO, Meuwissen MP, van Arendonk JA. A multi-level hierarchic Markov process with Bayesian updating for herd optimization and simulation in dairy cattle. *J Dairy Sci.* (2011) 94:5938–62. doi: 10.3168/jds.2011-4258
26. DeLorenzo M, Spreen T, Bryan G, Beede D, Van Arendonk J. Optimizing model: insemination, replacement, seasonal production, and cash flow. *J Dairy Sci.* (1992) 75:885–96. doi: 10.3168/jds.S0022-0302(92)77829-1
27. FAWC, Farm Animal Welfare Council. (2009). *Opinion on the Welfare of the Dairy Cow*. London. Available online at: https://www.gov.uk/government/publications/fawc-opinion-on-dairy-cow-welfare (accessed December 15, 2020).

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.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 14 April 2021
doi: 10.3389/fvets.2021.642126

A Comparison of Perceptions of Estonian and Latvian Hunters With Regard to the Control of African Swine Fever

*Nico Urner, Carola Sauter-Louis, Christoph Staubach, Franz Josef Conraths and Katja Schulz**

Friedrich-Loeffler-Institut, Federal Research Institute for Animal Health, Institute of Epidemiology, Greifswald, Germany

OPEN ACCESS

Edited by:
Céline Faverjon, Ausvet, France

Reviewed by:
Giovanni Cilia, Council for Agricultural and Economics Research (CREA), Italy
Kathleen O'Hara, University of California, Davis, United States

***Correspondence:**
Katja Schulz
katja.schulz@fli.de

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: *15 December 2020*
Accepted: *19 March 2021*
Published: *14 April 2021*

Citation:
Urner N, Sauter-Louis C, Staubach C, Conraths FJ and Schulz K (2021) A Comparison of Perceptions of Estonian and Latvian Hunters With Regard to the Control of African Swine Fever. Front. Vet. Sci. 8:642126. doi: 10.3389/fvets.2021.642126

Since the first detected African swine fever (ASF) cases in Lithuanian wild boar in 2014, the virus has occurred in many other member states of the European Union (EU), most recently in Belgium in 2018 and in Germany in 2020. Passive surveillance and various control measures are implemented as part of the strategy to stop disease spread in the wild boar population. Within this framework, hunters perform important activities, such as the removal of carcasses, fencing or hunting. Therefore, the successful implementation of these measures largely depends on their acceptability by hunters. Methods of participatory epidemiology can be used to determine the acceptance of control measures. The use of participatory methods allows the involvement of key stakeholders in the design, the implementation and the analysis of control and surveillance activities. In the present study, two studies that had been conducted using participatory epidemiology with hunters in Estonia and Latvia were compared on the topics recruitment, participants, facilitators, focus group discussion (FGDs) and their contents. The aim was to evaluate similarities and differences in the two studies and to identify a broader spectrum of possibilities to increase the willingness of hunters supporting the fight against ASF. Evaluating all conducted FGDs in both countries showed primarily similarities in the perceptions and opinions of the hunters in Estonia and Latvia. One notable difference was that passive surveillance in Latvia was perceived mostly as topic of duty and ethics rather than an issue driven by incentives. Participatory methods have proven to be an effective tool in the evaluation of the acceptance of established ASF control systems. The results of this study point out further chances for improving the cooperation with hunters in the future. Nevertheless, the importance of gathering and analyzing the opinions of hunters in all ASF affected countries individually is highlighted.

Keywords: African swine fever, participatory epidemiology, control measures, passive surveillance, acceptability, hunter, wild boar

INTRODUCTION

The recent entry of African swine fever (ASF) into Germany in September 2020 showed that the ASF spread in the European Union has not yet come to a hold (1). Since the beginning of the current epidemic in Georgia in 2007, more and more wild boar and domestic pigs have become infected globally (2). The ASF virus emerged in Lithuania, Poland, Latvia and Estonia as the first affected member states in the Eastern part of the EU (3). Currently, there are two main mechanisms, which are deemed to be responsible for the spread of ASF, i.e., trans-regional human mediated virus spread, sometimes over long distances, and local transmission by migrating wild boar (3–5). The potential role of wild boar as a susceptible species in the spread of ASF emphasizes the importance of establishing measures aimed at controlling local wild boar populations (2, 6–10).

Hunters belong to the most important stakeholders in the implementation of ASF control measures in the wild boar population (11, 12). Their regular presence in the forest, their experience and knowledge regarding local wildlife make them valuable partners with regard to control measures and passive surveillance. So far, hunters have been primarily involved in the implementation of mandatory processes, such as wild boar carcass searches, removal of carcasses from the environment and shooting wild boar. However, expert knowledge on the local situation, also with respect to the peculiarities of the wild boar population, is an important basis for the control of the ASF (11, 13). As mentioned by experts, hunters should therefore be included in the decision-making process (2, 14). This can be achieved by using methods of participatory epidemiology (PE) (15, 16). PE allows the involvement of stakeholders, e.g., in data collection or decision making on topics relevant for the community (11, 14, 17, 18). Participatory methods such as focus group discussions (FGDs) in combination with visualization or ranking and scoring tools are widely used in developing countries to support quantitative data generation in rural areas (13, 17, 19–22). Despite its potential in considering issues from different points of view and implementing specific local measures avoiding unpopular approaches, PE has not frequently been used in developed countries so far (17, 23).

To employ the advantages of PE by investigating perceptions of hunters and thus learning more about their motivations or reasons for hindrance to support ASF control in wild boar, two PE studies were conducted in Estonia and Latvia. In both studies, the same methods of FGD and visualization methods were used and regional opinions on the acceptance of ASF control measures and passive surveillance were collected and analyzed (24, 25). In the present study, the results of these two studies were compared, thus assessing similarities and differences. By comparing both studies, we aimed at identifying functioning processes and difficulties (26) in current control strategies against ASF, which may be addressed in future collaboration with hunters to increase the acceptance of passive surveillance and defined ASF control measures.

MATERIALS AND METHODS

Recruitment

Hunters from different areas in Estonia and Latvia were invited to participate. We intended to include a broad range of experiences and perceptions regarding ASF. In co-operation with hunting communities from Estonia and Latvia, leading hunters of regional hunting organizations were contacted. They were informed about PE and the aims of the studies and asked to invite hunters to the FGDs. In Latvia, staff of the "Latvian Food and Veterinary Service" contacted leading hunters. In Estonia, staff of the Veterinary and Food Laboratory contacted potential participants. The Veterinary and Food Laboratory is a facility, to which hunters regularly deliver samples.

Participants

It was planned to form ten FGDs per country with four to six participating hunters per group. The only requirement for participation was the willingness of the hunters to attend the meetings.

Facilitators and Focus Group Discussions

The participatory methods used by Urner et al. (24, 25) were adapted from Calba et al. (13) and Schulz et al. (11). The FGDs were divided into two tasks with regard to control measures and two tasks concerning passive surveillance. In each country, they were moderated by a national facilitator. The facilitators' responsibility was to introduce each task to the hunters and explain issues to avoid misunderstandings. In addition, the facilitators had the function to stimulate discussions and encourage reticent participants to express their views while moderating dominant participants. The facilitators were asked not to express their own personal view or to emphasize any particular opinion. The discussions were transcribed in Estonian and Latvian and translated into English.

Content

Acceptability of Control Measures

For the first task, the participating hunters were asked to enumerate all stakeholders they perceived as being part of the ASF control system. Subsequently, they were motivated to indicate the quantity of contacts from hunters to stakeholders and vice versa with four different arrows (no contact, little contact, normal contact, intensive contact). In addition, they were asked to rate the intensity of contacts qualitatively. To this end, each hunter assessed the contacts using smileys as good, neutral or bad (individual ratings). The last step of the first task was that the hunters were asked to use proportional piling to illustrate their trust in the stakeholders with respect to implementing control measures. For this purpose, the participants were given 100 glass beans, which they had to distribute among all stakeholders in proportion to their trust in the stakeholders to implement control measures appropriately (based on a consensus within the group).

In the second task, a list of six control measures was presented to the hunters [fencing, ban of hunting, including professionals for intensive hunting (police/army), increased hunting of female wild boar, incentives for hunting and increased carcass search and removal]. The participants were then asked to list additional measures, they could think of. All control measures were evaluated based on the hunters' satisfaction in implementing them (individual rating using smileys) and on the trust that the implementation of the measure might help to control ASF (consensus within the group, using proportional piling).

Acceptability of Passive Surveillance and Different Motivation Options

In the third task, the participants were asked to list positive and negative consequences that came to their mind when finding dead wild boar. Thereafter, the participants had to discuss until they had reached consensus and to evaluate the mentioned consequences by distributing 100 glass beans proportionally to the perceived impact the consequence would have on the hunters (proportional piling).

In the fourth task, four options to increase the motivation of hunters to participate in passive surveillance were presented to the hunters (increase of currently paid incentives, passive surveillance achieving the benefit of reduction of infection pressure in the wild boar population, only reporting dead wild boar without any further work for the hunter and detailed feedback from the relevant authority to the hunter). The participants were asked to add further options. Using proportional piling the hunters had to illustrate the potential of the options to motivate them to increase their engagement in passive surveillance.

Analysis

The results of the participatory methods were analyzed semi-quantitatively. To this end, the four different arrows were assigned to the numbers 0, 1, 2, 3 and the smileys to the numbers −1, 0, 1. For each option evaluated by these tools (stakeholders, control measures...), the average for all groups was calculated.

To evaluate proportional piling, a weighted average was calculated for each option (Stakeholder, control measures...). To calculate the trust T_{SHi} for a mentioned stakeholder (a) SH_i, the number of stakeholders mentioned in all groups SH, the number of groups which mentioned stakeholder (a) N_{SHi}, the number of stakeholders in the group in which stakeholder (a) was mentioned C_j^{SH} and the glass beans allocated to stakeholder (a) in each group GB_{ij} were taken into account. Details are described in Urner et al. (24, 25).

$$T_{SH_i} = \frac{1}{N_{SH_i}} \cdot \sum_{j=1}^{10} \frac{C_j^{SH}}{\sum_{j=1}^{10} C_j^{SH'}} \cdot GB_{ij},$$

The trust in a control measure to help control ASF, the impact of possible consequences on the hunters and the potential of an option to motivate hunters to participate in passive surveillance were calculated accordingly.

The results of the discussions were included descriptively.

The data and results from both countries were descriptively compared regarding the topics recruitment, participants, facilitators and FGDs.

RESULTS

Recruitment

The recruitment of participants were done similarly in both studies. A list of contact persons (leading hunters of local hunting clubs) had been provided by the national hunting organizations. These contact persons were contacted by phone or mail and informed about the aims of the study. The only difference was the organization that had contacted leading hunters of regional hunting organizations.

Participants

In total, 96 hunters participated, 46 in Estonia and 50 in Latvia. In each country, one woman participated. The age of the participants was no criteria for participation. To respect their personal rights and to keep the FGDs anonymous, they were not asked for their age. The estimated average age was 50 years.

Facilitator and Focus Group Discussions

Twenty FGDs were organized from May 2019 to July 2019. Ten FGDs took place in each country, with two to seven hunters per meeting. The group size did not differ in the two studies.

In Estonia, the facilitator was a female staff member of the Estonian University of Life Science, who had not worked with hunters previously and had not been involved in ASF control. She participated in a 3-day training school for participatory methods before the PE study started in Estonia. The study design was practiced under the guidance of the supervising author, who received PE training at the French Agricultural Research Centre for International Development (CIRAD) (11). In Estonia, only the facilitator attended the meetings. The discussions were therefore audio-recorded and afterwards transcribed by the facilitator. In Latvia, the facilitator was a female staff member of the Latvian Food and Veterinary Service, who had not worked with hunters previously and had not been involved in ASF control. The Latvian facilitator did not receive formal participatory training, but practiced the procedures during the discussions with the supervising author and the Estonian facilitator. The Latvian facilitator was assisted by two colleagues from the Latvian Food and Veterinary Service. One of them, a male colleague, was present as an observer and provided scientific background for questions regarding wild boar and the other one, a lady, transcribed the discussions. For analysis, the transcriptions were translated into English by the Language Centre of the Estonian University of Life Sciences in Estonia and the professional translator company "Skrivanek Baltic" in Latvia.

Contents

Acceptability of Control Measures

The listings and ratings of the stakeholders involved in controlling ASF of the Estonian and Latvian participants were similar (**Table 1**). In both countries, the minor contact to the research centers (Estonian University of Life Science and Institute BIOR) was perceived as unsatisfactory. Participants in both countries rated the police and the army as the least trustworthy organizations with one of the lowest contact rates.

Several stakeholders in society, such as the media, farmers and animal protection organizations were mentioned only in Latvia.

All hunters rated vaccination and hunting as the most trustworthy measures to control ASF and most satisfactory to implement (**Figure 1**). In Estonia, vaccination was not included in proportional piling by the facilitator as vaccination is currently not an option because there is no functional vaccine (27). Nevertheless, the hunters mentioned in the discussions that they would rate vaccination as the most trustworthy measure. The moral conflict of producing orphans by hunting female wild boar in the farrowing season was mentioned in discussions in both countries. The least trusted control measures in Estonia and Latvia overlapped as well (**Figure 1**). Similar reasons were mentioned, such as the hindrance of all game animals if a fence is built up. Implementing biosecurity measures during hunting was only mentioned in Latvia. It was trusted mediocre in controlling ASF and perceived satisfactory to implement. On the other hand, various hunting methods were mentioned only by Estonian participants. For example, bait feeding and shooting was highly trusted and considered satisfactory to implement.

TABLE 1 | The top five stakeholders rated by the participants to be the most trustworthy to implement control measures in an appropriate manner.

Estonia	Rank	Latvia
Hunters	1	Food and Veterinary Service
Veterinary and Food Laboratory	2	Hunters
Hunting Council of a county	3	Hunting organization
Estonian Hunters' Society	4	State Forest Service
Estonian University of Life Sciences (EMÜ)	5	Institute BIOR

Acceptability of Passive Surveillance and Different Motivation Options

The perceived consequences of finding dead wild boar overlapped in both countries. However, the assessment of the impact for hunters differed.

All participants mentioned consequences such as extra work, lost time, financial costs, recovering and disposing of the carcass. In Latvia, the perceived consequences focused on the fact that ASF can be controlled by searching carcasses (and removing them). This was mentioned as the "hunters' duty" in the discussions. In Estonia, the focus was rather on the negative consequences (**Figure 2**).

Comparing the proposed options to further increase participation in passive surveillance showed that in Estonia, an increase in financial incentives was considered more motivating than mere reporting with no further work. In Latvia, the pure idea of reducing the infection pressure in the wild boar population by searching for carcasses and removing them was considered the most motivating factor (**Figure 3**).

DISCUSSION

The success of ASF control measures and passive surveillance depends on the willingness of hunters to implement them (2, 11, 14). It is therefore of utmost importance that the national and international control of ASF focuses on identifying motivations or obstacles to support control measures and passive surveillance and, if necessary, on increasing the willingness of hunters to participate in these measures actively. To achieve this, PE methods should more frequently be included to complement conventional epidemiological approaches, also in industrialized countries. By integrating key stakeholders, decisions can be made based on extended information from the everyday life of those, who are directly affected and involved. However, this also

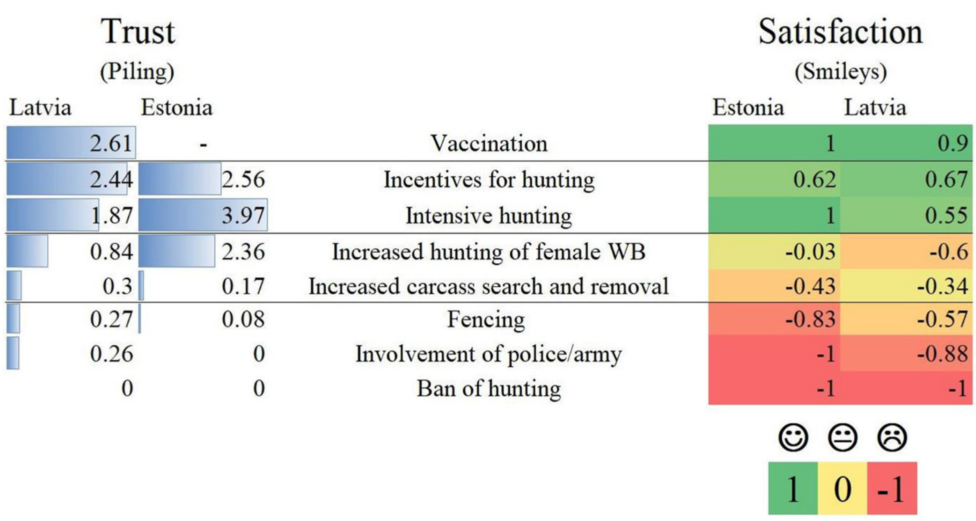


FIGURE 1 | Control measures rated by trust to control ASF and satisfaction in implementing them of Estonian and Latvian participants in ten focus group discussions comparison.

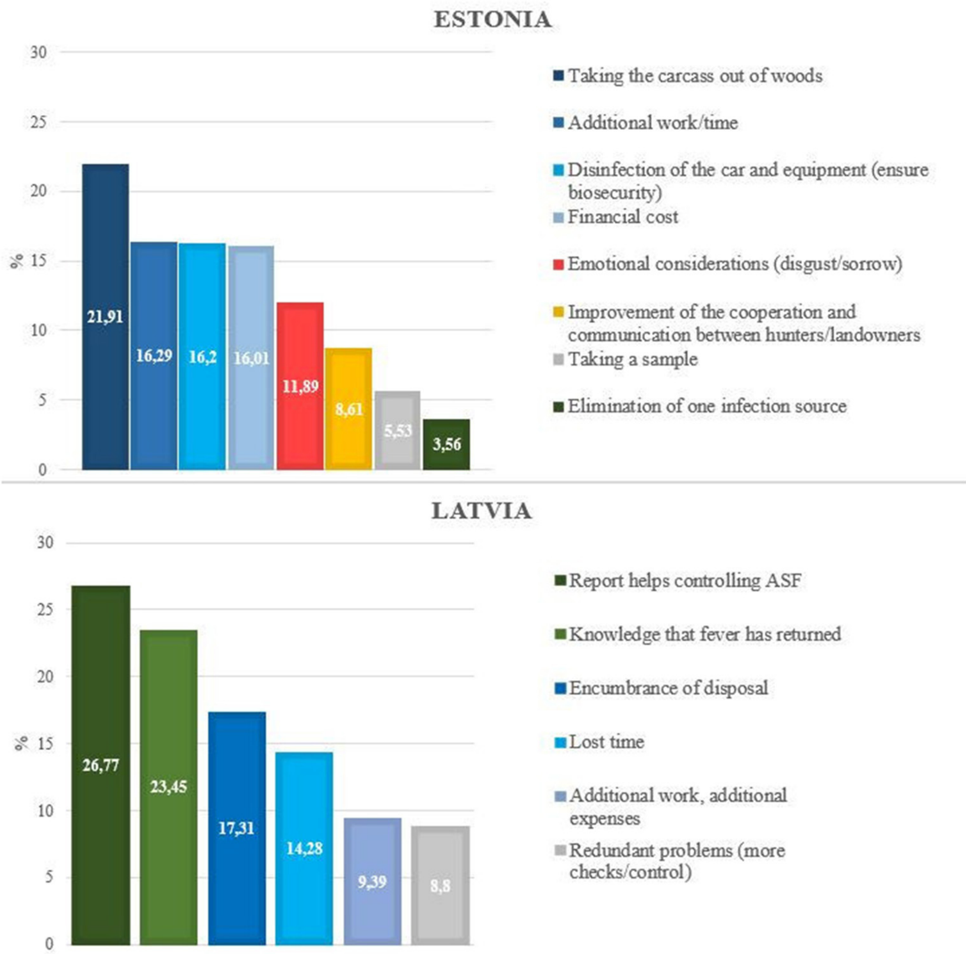


FIGURE 2 | Perceived extent of the impact by hunters of potential consequences when a dead boar is found, expressed as a percentage of all evaluated consequences in Estonia ($n = 46$) and Latvia ($n = 50$). The consequences are colored in green for ethical consequences, blue for consequences on time, work and money and reddish for emotional consequences.

influences the decision-making process by adding new biases, which are present in most participatory studies.

In the studies analyzed here, a potential selection bias may have been present due to the recruitment process (11, 13). Inviting participants through hunting associations holds the danger of recruiting only hunters of the direct social network of the contact person, who may share a common opinion. In addition, it is possible that mainly hunters were recruited, who were highly communicative toward hunting organizations and authorities (28). In addition, contact by the Ministry may have resulted in a situation, where some hunters felt compelled or obliged to participate and others may have been deterred. However, the roughly equal number of participants in both countries suggests that this bias has probably been low. The willingness to participate was therefore generally present and there was no obvious indication that hunters felt compelled to become involved. The total number of 96 participants may question the representability of the results. However, theoretical saturation was found in both studies as described in Glaser et al. (29) and Guest et al. (30). As the results were largely similar in both studies, which included hunters with a very different social background, the participation bias and question of representability may be regarded as minor.

Although the procedures to be followed by both facilitators were identical, a complete consistency cannot be guaranteed. Skills that characterize a good facilitator to get the most unfiltered results in a discussion could not be conveyed in short training provided to the facilitators (31), who also lacked experience in conducting PE studies. Furthermore, the openness of the participants toward an employee of a university (Estonia) might differ from the attitude toward an employee of a national authority (Latvia). In addition, there is the possibility that certain opinions may have been expressed in Latvia, precisely because the authority organized and carried out the FGDs. It seems possible that the hunters wanted to keep or create a certain image when confronted with a representative of a state authority or to

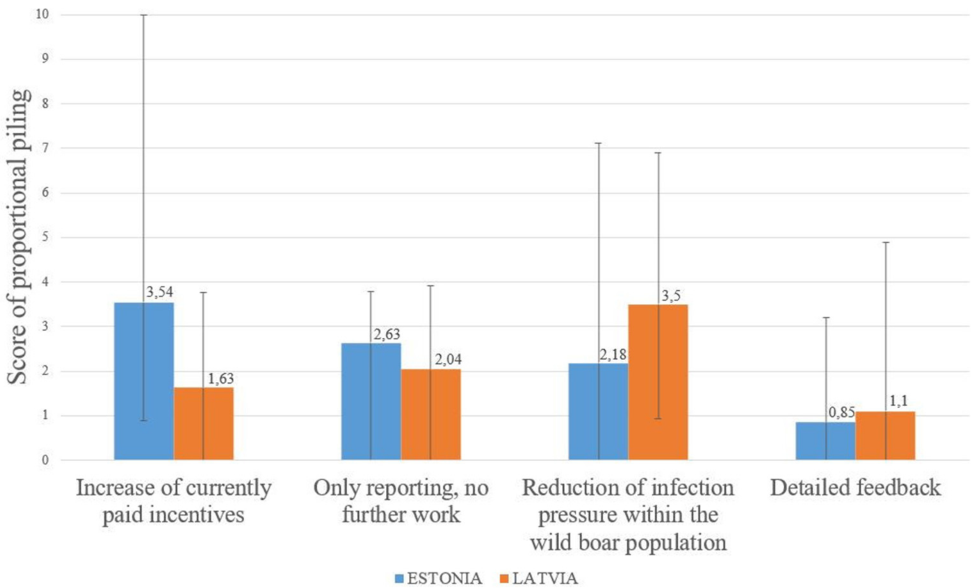


FIGURE 3 | Comparison of the perceived possible effectiveness of tools to increase participation in passive surveillance based on the calculated weighted average of the proportional piling. The average of all groups is displayed along with the range between minimum and maximum value of the weighted piles.

stimulate certain reactions by the authority. As a male employee working in ASF disease control was present in the Latvian FGDs for questions and misunderstandings, this may have influenced hunters' statements. However, the general overlap of the results suggests that this potential bias had little impact on the outcome.

Direct transcription in Latvia instead of recording in Estonia had the advantage that no further transcript had to be made from the audio recording. However, direct transcribing the contents of the FDGs might have led to a loss of information due to subjectivity, as it is very likely that not every spoken word was considered important, so that some statements could have been missed. The translation process of both transcripts into English might have caused some information loss (translation bias).

Diverging extraneous circumstances like substantial differences in ASF control, varying hunting structures and the biases discussed above prevent that a detailed statistical analysis adds value to the conclusions that can be drawn by a simple descriptive comparison. Moreover, several results were only available in a qualitative form, which made a statistical comparison not only extremely difficult, but also and not very telling. We therefore focused on the purely descriptive comparison. Despite these potential biases, the statements of the participants in Estonia and Latvia showed similarities. For some topics, almost identical statements were made. This does not only show the strong and similar opinions of the hunters, but also suggests that these biases can be regarded as minor.

The acceptance of working with stakeholders in the hunters' network strongly overlapped in both studies. This indicated relationships, which may be utilized and improved. Various possible co-operations (e.g., support from the army) should be discussed in advance with the hunters; otherwise they might feel not sufficiently respected in their main competence, i.e., hunting. It could be discussed, for example, that the army/police might only support carcass search and not hunting, which may subsequently lead to a higher acceptance of this measure by the hunters. Furthermore, the dissatisfaction with the small numbers of contacts with the research centers became obvious. This again supports the importance of communication, also with regard to scientific exchange before implementing measures. The differences in the networks of hunters in the two countries appeared to be small. The lack of mentioning various public stakeholders (e.g., animal welfare organizations, media) in Estonia compared to the ones mentioned in Latvia, could be explained by a different perception of the participants, who the relevant stakeholders were, or by a difference in the network of ASF control in Latvia.

The clear trend of acceptance of specific control measures was present in both countries, indicating a similar attitude of hunters, regardless of the individually implemented system of control measures. When interpreting the results, it must be taken into account that the two Baltic States are neighboring countries with a comparable recent history (32). Thus, the broad agreement in the perceptions and views of the hunters might be related to this neighborhood. To allow a more general statement about attitudes of hunters regarding ASF, it may be useful to implement the study in countries with more diverse geographical, historical and political background information.

Controlling ASF with hunting and increasing financial incentives for hunting is likely to find favor with hunters. Furthermore, the general acceptance of increasing incentives underlines the potential need of financial support for arising costs, such as equipment for biosecurity and transport. The same reasons given for not accepting fences (restricting other wildlife) and hunting female wild boar (morally contradictory to produce orphans in the farrowing season) reflect the common concerns of the hunting community and should be solved if these measures are to be implemented. Additionally, the high acceptance of vaccination and low acceptance of increased carcass search show how important scientific exchange is, especially on these specific topics to discuss effectiveness and in the case of vaccination availability (2, 7, 9, 27).

The fact that only in Latvia biosecurity during hunting was mentioned as a measure and only in Estonia several specific hunting methods were listed might show the different prioritization or awareness of control measures in the two countries. Biosecurity was mentioned in Estonia not before discussing passive surveillance and transporting carcasses. Thus, the awareness of hunters that biosecurity is appropriate in any handling of wild boar should be increased accordingly. However, it should also be considered that in Estonia, hunters just forgot to mention biosecurity as a control measure without any indication for the general perceived importance of biosecurity measures in Estonia.

The findings of Calba et al. (13) and Schulz et al. (11) that passive surveillance might not be highly accepted among hunters are supported by the perceptions of the hunters in the compared studies. Negative consequences such as increased workload, costs and time consumption were the focus in both countries. Reducing these hindering factors or even preventing them from occurring in the first place could significantly increase the acceptance of passive surveillance. All participants mentioned the same following approaches in this regard. Accordingly, the increase of financial support and the involvement of the army/police under the guidance of the hunters should be focused. In this respect, according to the participants, the emphasis should be on reducing the obligations of hunters. The implemented feedback systems seem to be sufficient, as additional detailed feedback was perceived not to be highly motivating in both countries. Thereby, increasing the details of feedback would only increase the workload for the veterinary laboratories without achieving higher participation rates in passive surveillance.

Despite the importance of eliminating negative consequences, Latvian hunters were more motivated by their moral obligation to participate in passive surveillance in order to contain ASF. This difference may have been caused by a potential bias of the observer from the Latvian authority. As mentioned before, the presence of the Latvian authority may have motivated the hunters to make statements, which make them look favorable. On the other side, the self-image of hunters in Latvia as workers for nature and wildlife may be different from that in Estonia, as passive surveillance was more often described as "hunters' duty" during FGDs in Latvia. Since the assessment of the motivating options was only comparative, it is possible that the perceived obligation of hunters has a similar status in Estonia, but the lack of financial support was regarded as more significant. These differences emphasize the need to communicate with hunters in each country individually and with regard to their specific views and concerns.

In summary, two main issues could be identified, which should be considered in efforts to improving cooperation with hunters and thus supporting the joint fight against ASF.

First, communication and cooperation with hunters should be increased, especially when it comes to the decision-making process. Communication should also include the dialogue with research centers. Hunters would like to become involved in scientific discussion. This was mentioned by all participants. This will ensure that they are informed about the most recent research results on ASF by the researches themselves. On the other side, through a two-way communication, disease control will benefit from the expert knowledge of hunters in implementing practical and successful control systems. In this context, workshops or training courses may largely support increased communication. These events could be very helpful to explain the reasons and the possible positive effects of measures to the hunters as executive stakeholders, especially regarding passive surveillance. Possible modifications of already implemented measures could also be communicated, discussed and adapted jointly, for example hunting female wild boars only in autumn and winter.

Secondly, loss of time and the increased workload are the main conflicting issues for hunters to contribute to passive surveillance. These issues could be addressed by having other external stakeholders supporting the hunters by taking over the collection and disposal of wild boar carcasses after a hunter has reported the finding. If this is not possible, financial incentives or compensations may be increased to cover costs and time.

This study describes hunters' opinions regarding passive surveillance of ASF and measures to control ASF in two EU member states affected by the disease. In essence, despite different systems of ASF control and the different hunting structures in the EU member states there was broad consensus on a large number of issues in the hunting communities of Latvia and Estonia. The results of this study may be incorporated with caution into future work on ASF control, as they only reflect the opinions of a single stakeholder group. Participatory studies including stakeholders involved in ASF surveillance and control other than hunters should also be conducted or these groups included.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

NU drafted the manuscript for this comparing study. KS, CS-L, CS, and FC provided scientific input and background for the draft of the manuscript and revised it extensively. All authors contributed to the article and approved the submitted version.

ACKNOWLEDGMENTS

We thank all the participating hunters of our study, as well as all our colleagues from the Baltic States, who supported us energetically.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.642126/full#supplementary-material

REFERENCES

1. Sauter-Louis C, Forth JH, Probst C, Staubach C, Hlinak A, Rudovsky A, et al. Joining the club: First detection of African swine fever in wild boar in Germany. *Transbound Emerg Dis.* (2020). doi: 10.1111/tbed.13890. [Epub ahead of print].
2. EFSA. Scientific Opinion - African swine fever in wild boar. *EFSA J.* (2018) 16:5344. doi: 10.2903/j.efsa.2018.5344
3. EFSA. Scientific Report - Epidemiological analyses of African swine fever in the European Union (November 2017 until November 2018). *EFSA J.* (2018) 16:5494. doi: 10.2903/j.efsa.2018.5494
4. EFSA. Scientific Opinion - African swine fever - EFSA panel on animal health and welfare (AHAW). *EFSA J.* (2015) 13:4163. doi: 10.2903/j.efsa.2015.4163
5. Podgorski T, Smietanka K. Do wild boar movements drive the spread of African Swine Fever? *Transbound Emerg Dis.* (2018) 65:1588–96. doi: 10.1111/tbed.12910
6. Depner K, Staubach C, Probst C, Globig A, Blome S, Dietze K, et al. African Swine fever - epidemiological considerations and consequences for disease control. *Tieraerztl Umschau.* (2016) 71:72–8.
7. Nurmoja I, Schulz K, Staubach C, Sauter-Louis C, Depner K, Conraths FJ, et al. Development of African swine fever epidemic among wild boar in Estonia - two different areas in the epidemiological focus. *Sci Rep.* (2017) 7:12562. doi: 10.1038/s41598-017-12952-w
8. Pejsak Z, Niemczuk K, Frant M, Mazur M, Pomorska-Mol M, Zietek-Barszcz A, et al. Four years of African swine fever in Poland. New insights into epidemiology and prognosis of future disease spread. *Pol J Vet Sci.* (2018) 21:835–41. doi: 10.24425/pjvs.2018.125598
9. Schulz K, Olsevskis E, Staubach C, Lamberga K, Serzants M, Cvetkova S, et al. Epidemiological evaluation of Latvian control measures for African swine fever in wild boar on the basis of surveillance data. *Sci Rep.* (2019) 9:4189. doi: 10.1038/s41598-019-40962-3
10. Olsevskis E, Schulz K, Staubach C, Serzants M, Lamberga K, Pule D, et al. African swine fever in Latvian wild boar-A step closer to elimination. *Transbound Emerg Dis*. (2020) 67:2615–29. doi: 10.1111/tbed.13611
11. Schulz K, Calba C, Peyre M, Staubach C, Conraths FJ. Hunters' acceptability of the surveillance system and alternative surveillance strategies for classical swine fever in wild boar - a participatory approach. *BMC Vet Res.* (2016) 12:187. doi: 10.1186/s12917-016-0822-5
12. Quirós-Fernández F, Marcos J, Acevedo P, Gortázar C. Hunters serving the ecosystem: the contribution of recreational hunting to wild boar population control. *Eur J Wildlife Res.* (2017) 63:57. doi: 10.1007/s10344-017-1107-4
13. Calba C, Antoine-Moussiaux N, Charrier F, Hendrikx P, Saegerman C, Peyre M, et al. Applying participatory approaches in the evaluation of surveillance systems: a pilot study on African swine fever surveillance in Corsica. *Prev Vet Med.* (2015) 122:389–98. doi: 10.1016/j.prevetmed.2015.10.001
14. Allepuz A, de Balogh K, Aguanno R, Heilmann M, Beltran-Alcrudo D. Review of participatory epidemiology practices in animal health (1980-2015) and future practice directions. *PLoS ONE.* (2017) 12:e0169198. doi: 10.1371/journal.pone.0169198
15. Bronner A, Hénaux V, Fortané N, Hendrikx P, Calavas D. Why do farmers and veterinarians not report all bovine abortions, as requested by the clinical brucellosis surveillance system in France? *BMC Vet Res.* (2014) 10:93. doi: 10.1186/1746-6148-10-93
16. McKerr C, Lo YC, Edeghere O, Bracebridge S. Evaluation of the national notifiable diseases surveillance system for dengue fever in Taiwan, 2010-2012. *PLoS Negl Trop Dis.* (2015) 9:e0003639. doi: 10.1371/journal.pntd.0003639
17. 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
18. Calba C, Goutard FL, Vanholme L, Antoine-Moussiaux N, Hendrikx P, Saegerman C. The added-value of using participatory approaches to assess the acceptability of surveillance systems: the case of bovine tuberculosis in Belgium. *PLoS ONE.* (2016) 11:e0159041. doi: 10.1371/journal.pone.0159041
19. Chambers R. The origins and practice of participatory rural appraisal. *World Dev.* (1994) 22:953–69. doi: 10.1016/0305-750X(94)90141-4
20. Roeder P, Rich K. *The Global Effort to Eradicate Rinderpest*. Washington: International Food Policy Research Institute (2013).
21. Reix CE, Dikshit AK, Hockenhull J, Parker RM, Banerjee A, Burn CC, et al. A two-year participatory intervention project with owners to reduce lameness and limb abnormalities in working horses in Jaipur, India. *PLoS ONE.* (2015) 10:e0124342. doi: 10.1371/journal.pone.0124342
22. Chenais E, Lewerin SS, Boqvist S, Stahl K, Alike S, Nokorach B, et al. Smallholders' perceptions on biosecurity and disease control in relation to African swine fever in an endemically infected area in Northern Uganda. *BMC Vet Res.* (2019) 15:279. doi: 10.1186/s12917-019-2005-7
23. Mariner JC, Jones BA, Hendrickx S, El Masry I, Jobre Y, Jost CC. Experiences in participatory surveillance and community-based reporting systems for H5N1 highly pathogenic avian influenza: a case study approach. *Ecohealth.* (2014) 11:22–35. doi: 10.1007/s10393-014-0916-0
24. Urner N, Motus K, Nurmoja I, Schulz J, Sauter-Louis C, Staubach C, et al. Hunters' acceptance of measures against African swine fever in wild boar in Estonia. *Prev Vet Med.* (2020) 182:105121. doi: 10.1016/j.prevetmed.2020.105121
25. Urner N, Serzants M, Uzule M, Sauter-Louis C, Staubach C, Lamberga K, et al. Hunters' view on the control of African swine fever in wild boar. A participatory study in Latvia. *Prev Vet Med.* (2020) 186:105229. doi: 10.1016/j.prevetmed.2020.105229
26. Sjoberg G. The comparative method in the social sciences. *Philos Sci.* (1955) 22:106–17. doi: 10.1086/287408
27. EFSA (2019). Risk assessment of African swine fever in the south-eastern countries of Europe. *EFSA J.* 17:5861. doi: 10.2903/j.efsa.2019.5861
28. Tripepi G, Jager KJ, Dekker FW, Zoccali C. Selection bias and information bias in clinical research. *Nephron Clin Pract.* (2010) 115:c94–99. doi: 10.1159/000312871
29. Glaser B, Strauss A, Hunger I, Müller J. *The Discovery of Grounded Theory: Strategies for Qualitative Research*. Chicago: Aldine Publishing Company (1967). p. 270S.
30. Guest G, Bunce A, Johnson L. How many interviews are enough? An experiment with data saturation and variability. *Field Methods.* (2006) 18:59–82. doi: 10.1177/1525822X05279903
31. Graef F, Sieber S. Cultural background, gender, and institutional status have an effect on the evaluation of multi-disciplinary participatory action research. *PLoS ONE*. (2018)13:e0196790. doi: 10.1371/journal.pone.0196790
32. Hackmann J, Brüggemann K, Urdze S, Regelmann AC, Pettai EC, Lang KO, et al. *Aus Politik und Zeitgeschichte - Estland, Lettland, Litauen*. bpb: Zeitschrift der Bundeszentrale für politische Bildung 8/2017 (2017).

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.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 16 April 2021
doi: 10.3389/fvets.2021.647697

Pig Farmers' Perceptions of Economic Incentives to Control *Salmonella* Prevalence at Herd Level

Jakob Vesterlund Olsen, Tove Christensen* and Jørgen Dejgaard Jensen

Department of Food and Resource Economics, University of Copenhagen, Copenhagen, Denmark

This paper investigates how perceived costs and benefits of *Salmonella* control among Danish pig farmers affect the farmers' choice of action toward reducing the prevalence of *Salmonella* in their herds. Based on data from an online questionnaire involving 163 Danish pig farmers, we find a considerable uncertainty among pig farmers about the perceived effects of the *Salmonella* reducing actions. The results indicate large variations in the perceived costs of implementing different types of *Salmonella* reducing actions (management-, hygiene- and feed-related). For some cases, farmers associate net benefits and positive productivity effects with implementation of the actions while studies by the industry indicate net costs to the farmers. Differences among farmers support the idea of an outcome-based *Salmonella* penalty scheme but the large uncertainties about costs and effects of actions toward *Salmonella* control might hamper the effectiveness of such a penalty scheme as a regulatory instrument to affect farmer behavior.

Keywords: questionnaire, *Salmonella*, economic incentives, zoonosis, pig farmers

Edited by:
Roswitha Merle,
Freie Universität Berlin, Germany

Reviewed by:
Estelle Ågren,
National Veterinary Institute, Sweden
Martin Wierup,
SLU, Sweden

****Correspondence:***
Tove Christensen
tove@ifro.ku.dk

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: *30 December 2020*
Accepted: *22 March 2021*
Published: *16 April 2021*

Citation:
Olsen JV, Christensen T and Jensen JD (2021) Pig Farmers' Perceptions of Economic Incentives to Control Salmonella Prevalence at Herd Level. Front. Vet. Sci. 8:647697. doi: 10.3389/fvets.2021.647697

INTRODUCTION

Salmonella is a zoonosis causing illness for many people globally. According to EFSA and ECDC (1), almost 88,000 confirmed cases of Salmonellosis in humans were reported in 2019 in the European Union. Poultry meat and eggs are the most prevalent sources of food-borne *Salmonella* contamination but pork is also a significant contributor to Salmonellosis in humans (2). *Salmonella* is typically not associated with clinical disease for pigs who are healthy carriers of the bacteria (3) but outbreaks of Salmonellosis among piglets can be associated with reduced daily weight gain (4). Overall, the prevalence of *Salmonella* bacteria does not *per se* incentivize farmers to reduce *Salmonella* on productivity grounds. Hence, the main costs of *Salmonella* in pigs and in pork seem to be carried by the consumers. As farmers do not have economic incentives to include risk of human infection from contaminated pork in their production decisions, human infections of Salmonellosis from eating pork can be considered an externality effect of pig production (5).

In order to reduce societal costs of human illness due to foodborne *Salmonella*, action plans have been initiated at EU level (6, 7) as well as at national levels (8). Denmark has had action plans for reducing the prevalence of *Salmonella* in pigs and in pork since 1995. The Danish approach to monitoring and controlling *Salmonella* in pork involves interventions in all parts of the food supply chain both at farm level, feed companies and at abattoirs. The goal is to maintain prevalence in carcasses below 1% (8, 9).

In 1998, Denmark introduced an economic penalty scheme where farmers pay a penalty when delivering pigs to the abattoir with high *Salmonella* prevalence (10). Thereby, direct economic incentives were introduced to motivate farmers who deliver pigs to the abattoirs to take action to reduce risks of carcasses containing *Salmonella* bacteria. While several studies suggest that controlling *Salmonella* at the abattoirs is more cost-effective than using farm level actions (9, 11, 12), they also stress the importance of keeping a low to moderate prevalence level at farm level (13, 14). Therefore, even though abattoir-level actions are more cost-effective, there seems to be a consensus to use a combination of pre- and post-harvest actions to reach target levels of *Salmonella* in pork (10, 15). The target level is keeping the prevalence of Salmonella below 1% of carcasses at the abattoir (16).

The *Salmonella* herd surveillance depends on whether it is a breeding herd, a sow herd or a finisher herd. All Danish herds delivering more than 200 finisher pigs to abattoirs per year are assigned a *Salmonella* level. The *Salmonella* level that can take the values one to three, with one being the best level without or with only low prevalence of *Salmonella*. The *Salmonella* level of a herd is determined at the abattoir, where a number of meat juice samples from each herd regularly are tested for antibodies against *Salmonella* using serological analysis (17, 18). If the sample shows that more than 40% of pigs from a herd are tested positive with antibody levels above a given threshold, the herd is placed in level two. If more than 65% of the pigs in a herd are tested positive, the herd is placed in level three. The percentages of positive tests are calculated as a weighted average of the last 3 months, with the latest month having a weight of 0.6, the month before a weight of 0.3 and the month prior to this a weight of 0.1.

The penalties that farmers delivering finisher pigs to the abattoir pay in a given month are determined by the assigned *Salmonella* levels. For pigs delivered from herds in level two, a penalty of 2% of production value is retained at the abattoir. The penalty increases to 4% of the production value being withheld for pigs from herds in level three. If the herd has been in level three for more than 6 months, the penalty increases to 6%. Finally, if slaughter pigs have been subject to a 6% penalty for more than 6 months and still is in level three, an 8% penalty is withheld at the abattoir. The scheme aims to induce pig farmers to think of *Salmonella* control as an economic problem where costs of implementing actions to reduce *Salmonella* risks at least to some extent are weighted against the benefits of having low levels of *Salmonella* in the herds. Here, avoided penalty constitutes the economic benefits of a low level of *Salmonella*. According to economic theory, the penalty scheme has the possibility to induce efficient reductions in *Salmonella* levels as it provides economic incentives for *Salmonella* control while at the same time allowing the individual farmers the freedom to choose the actions that are most cost-effective considering their specific herd characteristics**.** The penalty scheme provides a direct economic incentive for farmers who deliver finisher pigs to the abattoir to try to avoid *Salmonella*.

All pig herds (not only finisher herds) are placed in one of three *Salmonella* categories. Category A is for herds without *Salmonella*, category C is for herds that have *Salmonella* Typhimorium, Derby, Infantis, or Enterica while category B is for herds with other types of *Salmonella* than those grouped in category B (17, 19).

Sow herds are tested for *Salmonella* if the finisher herds they deliver piglets to are in level two or three. In this case, it is mandatory to conduct bacteriological testing of fecal samples in the sow herd delivering piglets. Thereby, information about *Salmonella* status of a sow herd is available for potential buyers of piglets. This information is intended to provide incentives for pig farmers to buy piglets from category A herds. It is not mandatory to buy piglets from category A herds but the information is available for owners of finisher pig herds if they want to do so.

Breeding herds are categorized as A, B, or C herds, based on serological testing of blood samples from young breeding animals (4–7 months old). If the tests indicate *Salmonella* prevalence above a given threshold, then also bacteriological testing of pen (fecal) samples are carried out (17).

A large number of studies have investigated risk factors for *Salmonella* prevalence in pig herds and actions to reduce *Salmonella* prevalence in pig herds. These include studies from Spain (20), Germany (21), Canada (22), the US (23), and Denmark (24–27). The studies point toward three overall types of actions for controlling *Salmonella* (28). One type of *Salmonella* control concerns the feed and water where for example adding organic acids to water and feed has shown to be protective against *Salmonella* while the use of pelleted feed is perceived to increase *Salmonella* risks (2, 15, 21, 23–27, 29, 30). A second type of *Salmonella* control actions relates to the management procedures where all-in/all-out production systems (31) and only buying *Salmonella* free piglets have been shown to reduce *Salmonella* prevalence in herds (32). The third type of farm-level *Salmonella* controlling actions includes hygiene-related actions such as intensive cleaning and disinfection of pens between batches and having a high level of rodent control (33, 34).

Alas, research findings are not always transformed into practice. One of the reasons could be lack of information flow from researchers to farmers. While there seems to be agreement among experts in Denmark (18) that many of the suggested actions can reduce *Salmonella* prevalence in pig herds, and also agreement among experts about which actions are the most effective, there is limited general advice of the effectiveness of the individual actions in practice on the individual farms. Other reasons for differences between research findings and practice among pig farmers regarding *Salmonella* control actions could include differences in farm specific costs of implementing *Salmonella* control actions (actual as well as perceived costs), additional resource costs for farmers in changing practices, mistrust in the perceived effectiveness of suggested control actions or lack of awareness of the problem (35). These potential reasons for not implementing available *Salmonella* controlling actions pinpoint the importance of involving social science in biosecurity research.

A few social science studies involving pig farmers' perceptions and self-reported behavior regarding biosecurity were found. Alarcon et al. (35) interviewed 20 British pig farmers and found that lack of awareness and knowledge regarding research scientific outputs being barriers for efficient control. Marier et al. (36) found in a British study involving four pig farmers, that the farmers did feel a responsibility for producing *Salmonella* free pigs but lacked confidence in the proposed control actions being effective. A Danish survey involving 138 pig and dairy farmers found that the farmers' were mainly motivated to improve their biosecurity by a desire to reduce the risk of having sick animals and to improve their economic performance and the welfare of their animals. Fewer in the sample of farmers mentioned legislation as a reason for improving biosecurity. The sampled farmers pointed toward a need for more practical solutions on how to prevent disease outbreaks in their herds (37).

We know that a number of actions for controlling *Salmonella* in herds are presently used and have been used by Danish farmers. However, as it is voluntary to choose which actions to implement it is not known how widespread the use of the individual actions are, why some farmers choose specific actions, and what rationales these choices are based upon. In particular, little is known about how economic incentives affect farmers to maintain a low level of *Salmonella* in their herds.

The overall purpose of the paper is to improve our understanding of the extent to which the economic incentives in Danish *Salmonella* action plan induce pig farmers to implement actions aiming to reduce the *Salmonella* prevalence in their herds. To address this overall research purpose, the following research questions (RQ) are answered with reference to Danish pig production:

RQ1 To what extent do existing expert-based estimates of costs and benefits of *Salmonella* control indicate incentives for reducing *Salmonella* prevalence at herd level?

RQ2 How do pig farmers perceive costs and benefits of *Salmonella* control?

RQ3 How are pig farmers' choice of action toward *Salmonella* control affected by attitudes and farm-specific factors?

The research questions were addressed using a combination of surveillance data and an online survey. The survey involved 163 Danish pig farmers with an over representation of farmers having experienced high *Salmonella* prevalence (more details about selection criteria are provided in the "Material and methods" section). Our contribution is to improve the understanding of pig farmers' perceptions and behavior toward *Salmonella* control actions at farm level using an economic framework of costs and benefits of *Salmonella* control. We view costs and benefits broader than direct changes in income and expenditures in that we include costs related to reluctance of changing habits, efforts involved in information acquisition and time resources as potential costs of *Salmonella* control. Moreover, we investigate to what extent differences in attitudes and herd specific characteristics can explain differences in choice of *Salmonella* control actions. We have studied Danish pig farmers as a case, with particular focus on investigating the incentives to control *Salmonella* induced by the Danish penalty scheme.

OVERVIEW OF *SALMONELLA* PREVALENCE IN DANISH PIG HERDS

An overview of the *Salmonella* levels of Danish pig herds between 2011 and 2018 is presented in **Table 1** using data from the Danish Central Husbandry Register (CHR) and the affiliated Danish Zoonosis Register. The CHR register holds information about where pigs are, how many pigs there are on each site, movement of pigs as well as registrations of veterinary events (38). The Danish Zoonosis Register holds information about the *Salmonella* status on a monthly basis for all pig herds with more than 200 pigs slaughtered per year in Denmark (39). In 2018, 85% of the farms remained at the lowest prevalence level throughout the year (level 1). Looking across all years and only including herds that have been in the dataset for at least 5 years, 43% of the herds stayed in level one throughout all years, 29% were at some point in time in level two but not in level three and 28% had been in level three.

With only 4% being in *Salmonella* level three in 2018 but 28% having been in level three at some point during a period of at least 5 years indicates that it is not the same farms which are constantly in level three. This observation is supported by statistics in **Table 2**, which shows that herds are around 2 months (on average) in *Salmonella* level two or three before they return to a lower level. The relatively short period of time in which herds have a higher *Salmonella* level could reflect that *Salmonella* in a herd dies out without reference to *Salmonella* control initiatives thereby contributing to improved *Salmonella* status. It could also reflect that farmers successfully have implemented actions attempting to reduce the *Salmonella* prevalence in their herds incentivized, possibly by the penalty scheme, to do so. The relatively large percentage of herds that have been in *Salmonella* levels two or three over the years could also point toward a great deal of randomness surrounding the *Salmonella* prevalence in the herds.

THEORETICAL FRAMEWORK

The empirical estimations of costs and benefits of *Salmonella* control at farm level and the inclusion of attitudes and perceptions were guided by a theoretical economic model. The model describes pig farmers' choice of *Salmonella* control actions in a stochastic setting. We take as a starting point that farmers seek to maximize their expected profit per finisher pig. A partial comparative static model is used where the only choice variable is the level of *Salmonella* control a, which can be influenced through a set of actions, x. We assume that *Salmonella* prevalence $s(a)$ is a decreasing function of *Salmonella* control a. Uncertainty about the effect of *Salmonella* control is captured by assuming that the *Salmonella* prevalence is a stochastic function of control level a, which in turn is a function of actions x, with the cumulative distribution function F as shown in Equation (1):

$$P\left(s \leq S \mid a(x)\right) = F\left(S \mid a(x)\right) \quad (1)$$

Costs associated with *Salmonella* controlling actions are captured by a function $c(x)$. Costs due to changed feeding or management might involve costs in terms of reduced feed conversion rates, increased use of labor and/or antibiotics. Potential changes in production output due to changes in *Salmonella* prevalence were also incorporated although in the case of Danish pig production it is usually not assumed that the *Salmonella* prevalence has an effect on output level (11). Production output, which is the number of pigs for slaughter, is a function of *Salmonella* control action $y(x)$.

TABLE 1 | Distribution of Danish pig herds according to their *Salmonella* levels based on highest level during a year.

Description	No. of herds	*Salmonella* status [percent of herds]		
		Level 1	Level 2	Level 3
Highest *Salmonella* level in 2018	8,459	85%	11%	4%
Highest *Salmonella* level (2011–2018)	5,074	43%	29%	28%

Level 1: sero-prevalence <40, level 2 sero-prevalence between 40 and 65, level 3: sero-prevalence >65. Data: 2011–2018. Only the 5,074 herds that have been in the dataset for at least 5 years from 2011 through 2018 are included in the latter calculation. Own calculations based on data from the Danish Zoonosis Register.

TABLE 2 | Estimated period that a Danish pig herd has a high *Salmonella* level.

Shift of level	Days	Herds
From 3 to 2	55.3	955
From 3 to 1	70.3	1,054
From 2 to 1	65.0	3,049

Own calculations based on data from the Danish Zoonosis Register. Data from 2011 to 2018. Only the 5,074 herds that have been in the dataset for at least 5 years from 2011 through 2018 are included in the calculation.

The *Salmonella* penalty scheme is included in the theoretical framework as a reduction in payments if *Salmonella* prevalence exceeds a certain threshold mimicking a shift from level one to level two (or from level two to level three). If the *Salmonella* prevalence is above a threshold $\overline{S}$ (i.e., $s \geq \overline{S}$), a penalty in the form of the price reduction δ per pig is levied on the producer. The price per pig is denoted p. Given these assumptions, the producer's expected profit function per finisher pig can be written as Equation (2):

$$E\left[\pi\ (a)\right] = \left(F\left(\overline{S}\,|a\left(x\right)\right)\cdot p + \left(1 - F\left(\overline{S}\,|a\left(x\right)\ \right)\right)\cdot\left(p-\delta\right)\right)\cdot y\left(x\right) - c\left(x\ \right) \quad (2)$$

The first-order derivative of this profit function with respect to the intervention action x_j

$$\frac{\partial E\left[\pi\right]}{\partial x_j} = \frac{\partial F}{\partial a}\frac{\partial a}{\partial x_j}\cdot\delta\cdot y\left(x\right) + \left(\left(p-\delta\right) + F\left(\overline{S}\,|a\left(x\right)\right)\cdot\delta\right)\cdot\frac{\partial y}{\partial a}\frac{\partial a}{\partial x_j} - \frac{\partial c}{\partial x_j} \quad (3)$$

The derivative with respect to action x_j represents the net increase in expected profit due to the action. If the derivative is positive, it will be expected to be profitable for the farmer to undertake action x_j, whereas it is not expected to be profitable if the derivative is negative. This derivative represents the change in expected profit due to a change in the action variable and has three main components:

a) Effect on the expected sales price due to changed probability of facing price penalty δ, which is affected by the impact of x_j on the *Salmonella* prevalence distribution.
b) Effect on the output (number of finisher pigs).
c) Effect on control costs per finisher pig.

This theoretical framework captures some of the complexities in a real decision process in that the decision to undertake action x_j reflects the farmer's trade-off between these three components. Additionally, the model captures that there may be uncertainty about all of the variables and that control decisions will often to some extent rely on the farmer's subjective perception of these components.

If the functional forms of the distribution function $F\left(\overline{S}\,|a\right)$, and of the *Salmonella* control $a\left(x\right)$ were specified, Equation (3) could be rearranged and x_j could be identified as a function f_j :

$$x_j = \begin{cases} f_j\left(p, \delta, \frac{\partial y}{\partial x_j}, \frac{\partial c}{\partial x_j}\right),\ if\ \frac{\partial E[\pi]}{\partial x_j} > 0 \\ 0\ otherwise \end{cases} \quad (4)$$

To keep the concepts relatively simple and focus on the trade-offs between different effects of *Salmonella* control, we have formulated the theoretical model in a static version where development over time is not included. It may well be imagined that farmers use their experience in one period to improve their understanding of these effects over time. For example, if a price penalty encourages the farmer to undertake an action in one period, the farmer may gain insights in this action's impacts on output and costs which may then lead to updated perceptions of these effects in subsequent periods. Thereby, an action initially undertaken to avoid the price penalty could also prove to be economically attractive to maintain even after the herd is back in *Salmonella* level 1 again.

We now turn to a description of the empirical analyses. They involve a description of data sources and how we have used them to answer the research questions.

MATERIALS AND METHODS

Data and Method Used to Address RQ1

Costs of *Salmonella* Control

Altogether, 12 *Salmonella* controlling actions were included in the analysis based on the literature study (27, 40–43) and interviews with two experts from the pig sector. The actions represent management, hygiene and feed actions. See **Table 3**.

The cost analyses were carried out as partial analyses with the implicit assumption that costs of implementing multiple *Salmonella* controlling actions are found by adding costs of individual actions. As there might be synergies when implementing multiple actions, this approach is likely to overstate aggregated costs. On the other hand, the only cost data available are based on farm trials where actions have been

TABLE 3 | Description of the 12 *Salmonella* actions and the types of costs involved.

Action	Description of types of costs
Buy pigs from herds with low *Salmonella* level	More expensive piglets. Some pig farmers include in their contracts that piglet sellers pay the penalty if the finishers are subject to penalty at the abattoir (44). Costs not estimated.
All in-all out/systematic shifting of batches	Only some stables are suitable for all in-all out shifts. It requires that finisher stable is divided into sections. We assumed that all new or renovated stables use this action as it has productivity gains (42). Costs are not estimated as it will not be implemented in stables that are not build for it already and for new buildings, the action will be implemented for productivity reasons.
Extra good hygiene when new batches are introduced	Additional labor costs. We have assumed that a herd with 200 finishers at a time in each section use 2 h additional cleaning between batches with hourly rate at 25.6 Euro/h (45). Additional expenses to material electricity and a high-pressure cleaner are estimated to 13.4 Euro/batch or 34 Eurocents/finisher.
Feed with organic acid	Direct expenses for adding organic acid to the feed for a finisher are estimated to 1.23 Euro per finisher.
Using fermented dry feed	Costs not estimated due to lack of data.
Using fermented wet feed	Costs of using fermented wet feed by using a fermentation tank. Reduced (better) feed conversion ratio is expected but still net costs of 40 cents per finisher due to investments in fermentation tank etc. (43)
Rough milled feed	Costs depend on how roughly milled the feed is and whether home-mixed or readymade feed is used. The costs are mainly related to increased feed conversion ratio. We have estimated the costs to 1.21 Euro per finisher based on results from Jørgensen et al. (26) and Sloth et al. (40).
Feed with high barley content	Costs due to increased feed conversion ratio. Estimated costs of 94 cents per finisher pig based on Jørgensen et al. (27).
Home mixed feed	Costs of using home mixed feed depend highly on whether the farmers has the facilities to do so. Hence, the costs are difficult to convert to variable costs per finisher. Costs are not estimated.
Acidified drinking water	Direct expenses for buying acids that is added to the drinking water. In some cases also capital costs are needed for investing in a mixer. Additional capital costs might be needed if the pipes must be changed to a non-corrosive material. If pipes are not changed, then we estimate that costs for a finisher are 1.32 Euro/finisher. Otherwise, costs are higher.
High hygiene for workers, visitors, dogs, cats, tools	Primarily, labor costs. For an average farm with an extra use of labor of 10 min per day this is estimated to be 28 cents/finisher.
Rodent control	Subscription costs for private rodent control company to supervise and eradicate rodents on the farm. Costs depend on farm size. Costs estimated to 13 Eurocents/finisher for an average farm.

Own calculations based on literature.

implemented as it is likely that such farms have lower than average costs. This part of the estimation might understate cost estimates. It should be noted, that not only are the cost estimated uncertain, the effectiveness regarding the effect on *Salmonella* prevalence is also uncertain. Costs of *Salmonella* controlling actions include monetary expenses, estimates of required time allocated to carry out each action, and the effect on productivity. The estimated productivity losses or gains from implementing the individual actions are to a large degree based on the pig sectors' own estimates from the farm trials. As the trials were carried out to guide farmers to choose the most cost-effective action to control *Salmonella*, we do not expect systematic bias in the estimates obtained from experts working in the pig sector. **Table 3** presents the actions together with a short description of the types of costs included.

The farms do not have the same opportunities to implement all of the actions in the short run. As an example, farms where the production units are separated into sections have the options to reduce or even eliminate infection between batches. Therefore, an action as "All in-all out/systematic shifting of batches" is only realistically applicable in herds with separated sections. Only costs related to actions, which are applicable to all farmers are estimated. Consequently, costs for four actions were not calculated: All in-all out/systematic shifting of batches, buy piglets from herds with low *Salmonella* level, using fermented wet feed and using home mixed feed. The cost estimates are presented as industry averages.

Benefits of *Salmonella* Control

The benefit of *Salmonella* control is the money saved by not having to pay a penalty. Estimating benefits of the individual *Salmonella* controls would require data on the effectiveness of individual actions to reduce Salmonella prevalence. We do not have this kind of data. Instead, benefits of being in *Salmonella* level one as opposed to levels two or three have been estimated. Using this framework, cost estimates based on individual control actions are compared with benefits based on *Salmonella* prevalence in the herd. This approach is obviously not ideal but highlights the imperfect information that often is present when farmers have to make their decisions.

Costs of delivering pigs while being in *Salmonella* level two or three is a percentage of the price of a pig delivered to the abattoir. According to SEGES (46), the price for a standard pig is 134 Euro in 2017. The penalty scheme reduces payments per pig delivered for all pigs delivered in a batch when *Salmonella* prevalence in the herd is above the given limit. Thereby, the benefits depend on the number of pigs delivered to the abattoir, the *Salmonella* status of the herd, and the period of time that the herd has been in level two or three. In order to estimate the penalty costs at farm level for an average farm, we needed an indicator of the yearly production rather than the number of animals at a given point in time on the farm as registered in the CHR, so we used industry statistics to link number of animals to yearly production (46).

Data and Methods Used to Address RQ2 and RQ3

Data Collection

In order to address RQ2 and RQ3, a questionnaire survey was conducted in a sample of Danish pig farmers. Information about herd size, type of herd, and *Salmonella* level was available from the CHR and Zoonosis registers. Using the same categorization as the CHR, we included finisher production, integrated production (producing piglets, weaners and finishers), other production (e.g., piglets only, weaners only, piglets and weaners) and breeding herds. Thereby, we included producers who deliver pigs to the abattoir and consequently can be directly affected by a penalty (integrated and finisher productions) as well as producers who are not directly affected by the risk of a penalty (e.g., piglet producers and breeders). As there are rather few breeders, they are overrepresented in the sample. Furthermore, to make sure to enroll farmers with experience in dealing with *Salmonella*, herds in *Salmonella*-level two or three were also overrepresented in the sample. Altogether, we invited 440 pig herd owners to fill out the questionnaire. The distribution of the 440 herds and the distribution of farmers returning the questionnaire is shown in **Table 4**. The data were collected between November 16 and December 15 2018 using one re-invitation midways. With 163 herd owners returning the questionnaire, we obtained a response rate of 37%. Unfortunately, we do not have data on those who chose not to respond to the invitation.

The Questionnaire

The questionnaire addressed the frequency of undertaking various *Salmonella* reducing actions, the perceived effectiveness of the actions, and the perceived costs of the actions. The farmers were presented with 12 possible actions related to management procedures, hygiene and feed changes (corresponding to the actions listed in **Table 3**). Questions related to the 12 possible actions are shown below (questions 1–4). The questionnaire also included questions about feeding and flooring systems in the herds as these were identified as risk factors (questions 5 and 6). The precise wording for the used questions is shown in **Supplementary Material**.

Question 1: You will be introduced to a number of actions that might reduce Salmonella prevalence. For each of the mentioned actions, we ask you to state whether you think that the action has an effect on Salmonella prevalence, the prevalence of other diseases, productivity, or has no effect. You can tick off multiple effects.

- Response categories: It reduces *Salmonella* prevalence, it reduces prevalence of other diseases, it increases productivity, it has no effect, don't know.

Question 2: For each of the mentioned actions, we ask you to state whether you have previously or presently implemented that action with the purpose of keeping a low prevalence of Salmonella.

- Response categories: I am or have previously implemented this action, I have not tried to implement this action.

Question 3: For each of the mentioned actions, we ask you to state whether you think that action has reduced Salmonella prevalence.

- Response categories: I think it has an effect (it was not mandatory to answer).

Question 4: For each action, please state which types of costs you experience or think that you would experience if you implemented the action. You can tick off multiple types of costs for each action.

- The listed types of costs included: Time costs, lower productivity, running expenses, capital investments, costs of changing habits/cumbersome, requires new knowledge, no particular costs, don't know.

Question 5: Which feeding system is your main system to your finishers?

- Response categories: Home-mixed wet feed restricted quantity, wet feed based on purchased ready-mix restricted quantity, home-mixed dry feed with *ad libitum* quantity, dry feed based on purchased ready-mix with *ad libitum* quantity, other/multiple feeding systems.

Question 6: Which flooring system do you have for your finishers?

- Response categories: Solid floor in more than half of the area (and slatted in the remaining area), solid floor in less than half of the area, combination of drained and slatted floor, other/multiple flooring systems.

In order to keep the questionnaire short and manageable, the 12 actions that might reduce *Salmonella* prevalence were assessed individually thereby implicitly assuming that they are independent (both in terms of being implemented independently and that their effects are independent). This is not in line with practice. As a mitigating circumstance, the aim of the study was to investigate the perceived effects of the actions and not scientifically documented effects. We have assumed that even if effects and costs of actions are not independent, the farmers will be able to form an opinion of the effects and costs of each individual action.

We have not distinguished between actions according to whether they were implemented to prevent a low *Salmonella* prevalence from rising or to reduce a high level of *Salmonella* prevalence. In the first case, *Salmonella* prevalence would be a function of actions taken whereas in the latter case, the actions would be a function of observed *Salmonella* prevalence. Such a distinction can be difficult make in practice and we pondered that distinguishing between actions on this ground would prolong the questionnaire unnecessarily. Consequently, the farmers' responses might reflect a mix of both situations. Hence, a simultaneity issue could be present in the statistical analysis.

Methods

Research question RQ2 was investigated using descriptive statistics of Question 1 to Question 4 to document how widespread various beliefs are among pig farmers.

TABLE 4 | Distribution of Danish pig herds and of herds in the sample categorized according to *Salmonella* level.

	***Salmonella* level 1**	***Salmonella* level 2**	***Salmonella* level 3**	**Total**
Piglet production	811	58	20	889
Finisher pig production	1,856	298	101	2,255
Integrated production	87	23	5	115
Other production	422	72	34	528
Total	3,176	451	160	3,787
Invited in the survey	140	130	130	400
Respondents	52	45	48	145
Breeding herds invited				40
Breeding herds respondents				18
Respondents total				163

Herds with more than 60 finishers in stock (estimated to deliver more than 200 finishers in a year) were included. A total of 3,787 herds of which 400 were invited in the survey. Also 40 breeding herds were invited. They are listed separately as they do not deliver pigs for slaughter and are not assigned Salmonella levels. Data are from first half of 2018. 'Other production' includes e.g. herds with only sows and no weaners or only weaners without sows or finisher production.

Research question RQ3 was addressed by estimating the relationship between farmers' likelihood of undertaking a given action on the one hand and their perceptions of types of costs, the perceived effect of the action and central herd characteristics on the other hand. The statistical model was based on an empirical operationalization of Equation (4). To carry out the estimations, we assumed that decisions to implement *Salmonella* control actions were based on observing a given *Salmonella* prevalence in the herd. For each *Salmonella* control action, we used a logistic regression approach, where the likelihood (expressed as log-odds ratio) of the action being used (now or in the past) constituted the dependent variable. The following model was estimated for each action:

$$\log \frac{P(x=1)}{1-P(x=1)} = \beta_0 + \beta_1 \textit{Think effect} + \beta_2 \textit{ Niche} + \beta_3 \textit{ S.level2} + \beta_4 \textit{ S.level 3} + \beta_5 \textit{ Cost} + \beta_6 \textit{ Effect} + \beta_7 \textit{ Feed} + \beta_8 \textit{ Floor} + \varepsilon \quad (5)$$

The variable x is a dichotomous variable assuming the value 1 if the farmer uses or has used the action and 0 otherwise. The parameters $\beta_1, \ldots \beta_8$ capture the individual effects on the explanatory variables on the likelihood of implementing the action. The variable *Think effect* assumes the value 1 if the farmer associates a positive effect with the action toward *Salmonella* and 0 otherwise. The variable *Niche* assumes the value 1 if the herd is a breeding herd or has another high quality niche production and 0 otherwise. The variable *S. level 2* assumes the value 1 if the herd has been in *Salmonella* level two within the last 5 years, and *S. level 3* assumes the value 1 if the herd has been in *Salmonella* level three within the last 5 years–and zero otherwise. The variable *Cost* captures eight different types of perceived costs: time costs, reduced productivity, running expenses, investments, costs of changing habits, requires new knowledge, no particular costs, undecided. For each type of cost, the variable assumes the value 1 if the farmer associates that type of cost with the action and 0 otherwise. The variable *Effect* captures three types of perceived effects of the *Salmonella* control: reducing *Salmonella* prevalence, reducing prevalence of other diseases, or increasing productivity. For each type of effect, the variable assumes the value 1 if the farmer associates that effect with the action and 0 otherwise. The variable *Feed* captures the feeding system used in the herd from a list of five possible systems, taking the value 1 if a given feeding system is used and 0 otherwise. The variable *Floor* represents the flooring system used in the herd from a list of four possible types of floor taking the value 1 if a give flooring system is used and zero otherwise. Type of floor and elements of the feeding strategy are considered fixed in the short run but can be included as decision variables in a long run analysis.

The farmers' perceptions of productivity effects are represented in two different ways in the logistic regression. Firstly, one of the dummy variables in *Cost* is "reduced productivity." Secondly, one of the dummy variables in *Effect* is "it increases productivity."

The logistic regression analyses were only carried out for eight models of *Salmonella* controls. For four of the actions, there was too little variation. The actions not included are: the use of fermented feed (dry or wet); having high hygiene for workers, visitors, dogs, cats, tools; and rodent control. The logistic regressions were conducted using the software package R.

RESULTS AND DISCUSSION

Results and Discussions Related to RQ1

The costs related to actions that can be implemented in existing facilities on all farms are presented in **Table 5**. The actions are presented in ascending cost order per finisher pig. The penalties per pig are also included in **Table 5** to ease comparison between costs and benefits of *Salmonella* control actions. For a farmer with costs equal to the industry average costs, several actions could be implemented cheaper than the costs of paying the penalty for being in *Salmonella* level two. The five cheapest actions have aggregated costs lower than the penalty of 2%. Another two actions can be implemented at a lower cost than the 4% penalty. Finally, the last of the actions included in the cost estimation can be implemented

TABLE 5 | Industry cost estimates for applying on farm actions to reduce *Salmonella* prevalence and penalties for *Salmonella* prevalence (per finisher pig).

Action	Slaughter pigs [€-cent/pig]	Aggregated costs [€-cent/pig]
Have extra rodent control	13.4	
Maintain high hygiene standards	28.2	41.6
Have extra good hygiene before new batches are introduced	33.6	75.2
Use fermented wet feed	40.3	115.5
Use feed with high barley content	94	209.5
2% penalty		*258*
Use rough milled feed	120.8	330.3
Use acidified feed	123.5	454
4% penalty		*536*
Use acidified drinking water	131.5	585
6% penalty		*804*
8% penalty		*1,072*

*Detailed information about cost estimates can be found in **Table 3**.*

TABLE 6 | Share of farmers who use/have used the presented *Salmonella* reducing action and the share of farmers who think it has an effect (in percent of respondents).

	Being used	I think it has an effect
Buy pigs from herds with lowest *Salmonella* level	55	23
All in-all out	80	28
Have extra good hygiene between batches	91	23
Use acidified feed	74	29
Use fermented dry feed	9	11
Use fermented wet feed	16	16
Use rough milled feed	55	19
Use feed with high content of barley	61	18
Use home mixed feed rather than ready made	62	20
Use acidified drinking water	68	22
Have high hygiene for workers, visitors etc.	84	20
Have extra rodent control	95	21

One hundred and forty eight of the producers answered both questions and the shares shown in the table are shares out of 148 producers.

at a lower aggregated cost than the 6% penalty. Hence, based on average industry costs, **Table 5** indicates that farmers could initiate several actions with lower costs than paying the penalty of 2 or 4%.

Below we illustrate the effects of the penalty scheme at herd level. We provide two examples the size of penalties to be paid at the abattoir for an average farm delivering 10,000 finisher pigs per year (46):

Example 1: Six months in *Salmonella* level two induces a loss in income of 13,000 Euro in penalties.

Example 2: Six months in *Salmonella* level 2 and 6 months in level three induces a loss in income of 40,000 Euro in penalties.

These penalties can be considered as the benefits for a herd of staying in *Salmonella* level one, and thus they constitute the break-even amount to spend on *Salmonella*-reducing actions.

The average profit of a Danish pig farm provides a reference for the significance of the penalties. During the period between 2014 and 2017, a full time farm in Denmark had an average negative profit of 3,100 Euro ranging from minus 52,000 Euro in 2014 to plus 69,000 Euro in 2017. Thereby, the penalty scheme might have a significant effect on the farm economy.

As we do not know the effect of the action, the cost effectiveness is not known.

Results and Discussions Related to RQ2

With heterogeneity between herds, there might be farmers who do not view the costs and benefits of *Salmonella* control as estimated in **Table 5**. In order to address the potential variations among farmers, **Table 6** presents how widely the various actions are or have been used together with farmers' perceptions of the effectiveness of the actions.

Table 6 shows that most of the presented actions have been used widely in Danish pig farms. The hygiene-related actions are used by the vast majority of the farmers (more than 80% of the respondents) while acidification of feed or drinking water are used by three out of four of the respondents. The actions with the lowest uptake among farmers include fermented dry feed (used by 9% of the respondents) and fermented wet feed (used by 16% of the respondents). We also find that less than one third of the farmers believe that the individual actions are efficacious.

Differences among farmers regarding which control actions they use or have used might be related to the types of costs that farmers associate with the individual actions. **Table 7** sheds light on how perceptions of different types of costs associated with the 12 potential *Salmonella* reducing actions are distributed across farmers. Some farmers find it cumbersome to implement new actions due to change of habits ("Habits" in **Table 7**) and others associate costs with the need to obtain new knowledge to implement actions ("Knowledge" in **Table 7**). There are also farmers who do not associate particular costs with implementing new actions ("No particular" in **Table 7**).

An important observation from **Table 7** is that many of the farmers answered "Don't know" to the question of which costs they associated with the individual control actions. This results indicates that many farmers have not really thought about the costs which is potentially surprising given that many of the farmers have used the actions. Also, all actions have in common that only a small minority of the farmers perceive them as costly in terms of knowledge acquisition.

We observed differences across actions as well. For some of the actions, the associated costs are consistent with the expert-estimated cost described in **Tables 3**, **5**. The use of rough milled feed and higher barley content in the feed are associated with lower productivity by the farmers as well as by the experts.

TABLE 7 | Share of farmers who associate various types of costs with the presented *Salmonella* reducing actions (in percent of respondents).

Action	Time costs	Loss of productivity	Running expenses	Investment	Habits	Knowledge	No particular	Don't know
Buy pigs from herds with low *Salmonella*	2	2	26	8	4	2	39	26
All in-all out system	20	15	13	11	14	2	46	7
Extra good hygiene between batches	55	2	25	5	26	1	32	4
Acidification of feed	4	2	82	7	4	1	5	12
Fermented dry feed	2	1	23	12	1	4	1	64
Fermented wet feed	5	1	22	18	2	4	5	56
Rough milled feed	1	42	35	2	2	1	17	24
Feed with high content of barley	1	30	26	2	1	1	25	26
Home-mixed feed	23	1	15	38	12	5	23	20
Acidification of drinking water	17	3	73	17	12	1	6	15
High hygiene for workers, visitors etc.	30	1	14	6	14	2	54	10
Rodent control	22	1	64	2	11	1	23	6

One hundred and forty two of the producers answered this question.

Also, the associations of running costs with acidified feed and drinking water as well as with rodent control are in line with expert opinions. Another interesting observation is that for four of the actions, more than 30% of respondents did not associate implementation with extra costs. The four actions were "buy pigs from herds with low *Salmonella* level," "all in–all out" and the two hygiene-related actions. Around 20% of the respondents found no particular costs associated with the feed-related actions rough milled feed, feed with high content of barley and using home-mixed feed. As other farmers associated these actions with extra costs, our results indicate that actions are perceived to have very different costs across herds.

Differences in farmers' perceptions of the effects of various control actions and their costs might also be related to differences in disease pressure where management and hygiene actions might affect other diseases. Farmers' perceptions of whether the individual actions have an effect on *Salmonella* level, other diseases, productivity, or no effect is shown in **Table 8**.

For all actions, we note that only a small part of the farmers (between 3 and 9%) believes the action has no positive effect on either reducing the prevalence of *Salmonella* or of other diseases or on increasing productivity. All actions are associated with all types of effect to various degrees. All actions score high on their effect on *Salmonella* reduction. The only exception is fermented feed where less than one third of the sampled pig farmers believe it reduces *Salmonella* risk. Comparing the results presented in **Tables 6**, **8** reveals that significantly more farmers state the 12 listed actions to have a reducing effect on *Salmonella* prevalence (**Table 8**) than farmers stating that they have tried to implement the actions and that they believe that the actions have an effect (**Table 6**). Unfortunately, it is not possible to dig deeper into these differences where possible explanations could be the different wordings of the two questions and the order of the questions. Unexpectedly many "don't know" answers were found for fermentation-related actions (two out of three responses). This could indicate a high level of confusion about the question formulation or the action itself–or both.

Addressing RQ2, the most significant result is that less than one third of the farmers believe that the actions they have implemented to reduce *Salmonella* prevalence have had an effect. Hence, the perceived benefits of the *Salmonella* control actions are rather weak. A potential explanation, inspired by a respondent's comment to an open question in the questionnaire, was that as they often initiate multiple actions at the same time, they do not know which of the actions are effective. Secondly, an important result regarding perceived costs of *Salmonella* control actions is that running expenses are widely associated with all 12 listed actions. Thirdly, the feed-related actions regarding high content of barley or roughly milled feed are in particular associated with loss of productivity. Fourthly, many farmers in the sample link management-related actions and hygiene-related actions with not only reducing *Salmonella* prevalence but also with reducing the prevalence of other diseases as well as with increasing productivity. As a contrast, feed-related actions are mainly associated with reducing *Salmonella* prevalence.

Results and Discussions Related to RQ3

Potential explanatory factors for farmers' choice of using the listed *Salmonella* control actions are shown in **Table 9**. At the risk of information overload, we have included significant as well as in-significant variables from the regression analysis in **Table 9**. An advantage of keeping all explanatory variables in the model include that it eases comparison between actions and

TABLE 8 | Farmers' perception (in percent of respondents) of whether the individual actions have an effect on *Salmonella* level, other diseases, productivity, or no effect.

Action	Reduces *Salmonella* prevalence	Reduces other diseases	Increases productivity	No perceived effects	Don't know
Buy pigs from herds with low *Salmonella*	72	15	21	9	13
All in-all out/systematic shifting of batches	72	43	48	5	7
Extra good hygiene when new batches are introduced	79	48	47	3	3
Acidification of drinking water	84	17	21	4	15
Acidification of feed	15	2	6	8	71
Fermented dry feed	28	7	10	6	63
Fermented wet feed	60	22	4	8	20
Rough feed	48	20	7	9	34
Feed with high content of barley	53	11	11	5	35
Home-mixed feed instead of ready made feed	83	13	10	3	13
High hygiene for workers, visitors etc.	64	46	26	5	11
Rodent control	82	40	21	3	9

A total of 149 farmers answered this question.

that the sign of an insignificant factor also provides information about weak effects that with a larger data set might turn out significant.

A noteworthy result is that none of the variables related to perceived types of costs had a significant effect on whether an action was used. The only exception being that time costs had a negative effect on the use of acidified feed (as could be expected) but a positive effect on the use of acidified water (not as could be expected).

Having been in *Salmonella* level two or three had a significant and positive effect on the likelihood of using feed-related actions and of using acidified water. Believing that an action increased productivity also had a positive effect on all actions and significant for several. Only exception was the use of acid in water where a belief in increased productivity had a negative but in-significant effect.

As expected, across actions, a belief that an action had a *Salmonella* reducing effect had a significant and positive effect on the probability of using it. The only exception was increased hygiene between batches, where its use was not affected by whether the farmer perceived it to have a *Salmonella* reducing effect. We suggest that this result indicates that the farmers have other reasons than *Salmonella* concerns to increase hygiene between batches.

Farmers with breeding herds are more prone than other farmers to use all means to reduce *Salmonella* including actions estimated to be more expensive such as rough feed (see **Table 3**). This result is as expected as the costs to the breeding herds of not being able to sell their breeding animals are high. Thereby, breeding farmers have stronger incentives than other farmers to reduce *Salmonella* in their herds. Another statistically significant result is that farmers with special production are more prone to use the action "all in/all out," which is most likely due to a correlation between farmers who have special production also have barns that makes batch production relevant.

Less expected, we found that for most actions, the variable "I think it has an effect" has a negative and significant association with the decision to implement the action. We stress that we cannot draw conclusions on causality, but we would have expected the opposite, namely a positive correlation between a belief in that it has an effect and choosing an action. We have two possible explanations for the negative correlation. One reason for the negative correlation is that there is a great deal of confusion about the effects of the individual actions because multiple actions are often implemented simultaneously. Another possible reason is linked to the lack of time line in the data. Rather than looking at the result as farmers implementing a *Salmonella* control action even though they believe it does not have an effect, we could interpret the result as showing that farmers who are or have been implementing a given action have experienced that it does not reduce *Salmonella* prevalence. As the data do not allow us to distinguish between farmers who are implementing a given action and farmers who have done so in the past and thereby have an experience regarding its effectiveness, we cannot dig more into that possible reason (we thank an anonymous referee for suggesting this association). Further studies, possibly involving detailed interviews are needed to dig deeper into this apparent paradox.

Addressing RQ3, the overall picture was that perceptions of costs and effects and herd characteristics had a non-systematic effect on the implementation of 12 listed *Salmonella* reducing actions. A few central effects are nevertheless worth highlighting. First, farmers who believe that an action has a *Salmonella*-reducing effect or that it increases productivity are more likely than other farmers to choose that particular action. This suggests that the expected effectiveness of the action either on *Salmonella* prevalence or productivity is an important determinant for the choice of action. Also, we found that farmers who have been in *Salmonella* level two or three within the last 5 years were more prone to use acidified feed, acidified drinking water, and home mixed feed.

TABLE 9 | Logistic regression model explaining the choice of *Salmonella* control with variables related to perceptions of costs and effects, *Salmonella* level in the herds as well as herd characteristics.

	Buy pigs	**All in-all out**	**Hygiene new batch**	**Acid in feed**	**Rough feed**	**Barley feed**	**Home mix feed**	**Acid in water**
Constant	1.72 (1.95)	0.46 (1.81)	8.40* (4.00)	−20.3 (2,855)	−2.29 (1.27)	−2.85 (1.52)	−1.62 (1.41)	−4.07 (2.33)
Parameter estimates related to perceived types of costs (standard errors)								
Time costs	21 (1,471)	1.13 (1.19)	−1.41 (1.92)	−3.53* (1.69)	18.25 (6,523)	13.69 (3,378)	0.57 (0.93)	3.72** (1.34)
Productivity costs	1.66 (2.18)	−1.43 (1.21)	−42.38 (24,244)	−0.84 (3.29)	−0.31 (0.8)	0.57 (1.11)	0.88 (2.24)	−1.93 (1.76)
Running expenses	−2.07 (1.75)	−0.71 (1.3)	−1.35 (1.98)	17.93 (2,855)	0.29 (0.74)	1.38 (1.05)	0.53 (1.15)	−2.65 (1.81)
Investments	−2.89. (1.72)	−2.08 (1.29)	21.29 (5,115)	17.5 (1,931)	−16.32 (3,425)	16.09 (3,010)	−1.18 (1.19)	−2.29* (0.94)
Habits/ cumbersome	−19.04 (1,471)	0.79 (1.48)	−2.53 (1.78)	−2.44 (1.68)	34.9 (4,844)	17.34 (3,378)	1.06 (1.09)	−0.77 (1.42)
Knowledge	1.91 (2.4)	17.37 (1,947)	18.89 (10,220)	2.33 (4,272)	−23.34 (9,840)	15.13 (3,378)	−0.35 (1.72)	−1.46 (14.53)
No particular costs	−0.73 (1.58)	0.78 (1.28)	−2.18 (2.03)	18.41 (2,855)	−0.09 (1.06)	1.16 (1.28)	0.3 (1.38)	15.81 (1,620)
Don't know about costs	−3.74* (1.7)	−0.81 (1.5)	−4.39 (2.92)	16.1 (2,855)	−2.40* (1.03)	−1.12 (1.28)	−1.29 (1.25)	−4.25* (1.9)
Parameter estimates related to perceived effects (standard errors)								
Effect on *Salmonella*	1.62** (0.61)	2.10* (0.93)	3.37 (2.04)	2.7* (1.07)	1.82** (0.6)	2.22*** (0.59)	1.73* (0.68)	3.16** (1.05)
Effect on other diseases	0.45 (0.83)	−0.26 (0.95)	−2.16 (1.91)	0.2 (1.1)	0.22 (0.71)	0.35 (0.7)	1.13 (1.19)	5.43* (2.19)
Increases productivity	1.19 (0.82)	3.34** (1.29)	5.56* (2.3)	2.84* (1.33)	19.67 (2,267)	3.07* (1.33)	1.26 (1.22)	−0.80 (1.31)
I think it has an effect	−2.56*** (0.77)	−4.09*** (1.09)	−4.08* (1.93)	−1.82* (0.76)	−2.46** (0.78)	−2.89*** (0.84)	−1.04 (0.82)	−0.89 (0.97)
Parameter estimates related to *Salmonella* level and production system (standard errors)								
Level 2, past 5 yrs.	0.54 (0.71)	−0.33 (0.89)	−3.83 (2.48)	2.27** (0.78)	0.83 (0.7)	0.14 (0.74)	2.96** (1.03)	3.27** (1.06)
Level 3, past 5 yrs.	1.16 (0.87)	−0.12 (1.07)	−3.84 (2.71)	2.57** (0.89)	1.64* (0.81)	0.18 (0.79)	2.26* (0.94)	3.78** (1.19)
Breeding herd	−1.36 (1.07)	1.60 (1.40)	18.12 (3,712)	−0.57 (1.02)	4.56** (1.57)	2.29 (1.17)	0.10 (1.12)	1.61 (1.37)
Home mixed dry feed	−1.56* (0.76)	−2.31 (1.2)	−1.68 (2.16)	−0.50 (1.02)	−0.25 (0.67)	1.13 (0.72)	1.62 (1.24)	0.51 (0.87)
Other/multiple feeding systems	0.44 (1.23)	1.85 (1.93)	−4.40 (3.46)	2.06 (1.53)	0.37 (1.25)	−1.40 (1.09)	−1.27 (1.33)	−0.34 (1.33)
Wet feed, purchased	2.14 (1.34)	−1.94 (1.58)	−3.82 (2.97)	0.70 (1.23)	0.29 (1.22)	1.49 (1.37)	−1.19 (1.17)	4.02* (1.74)
Dry feed, purchased	0.67 (0.71)	−1.01 (1.08)	−3.67 (2.23)	−1.18 (0.96)	1.66* (0.70)	0.09 (0.7)	−3.27*** (0.9)	2.61* (1.04)
Special production	−0.78 (0.62)	2.84* (1.16)	0.32 (1.50)	−0.12 (0.82)	0.37 (0.62)	0.75 (0.71)	0.79 (0.87)	0.37 (0.84)
Max 50% solid floor	−1.36 (0.79)	0.53 (0.97)	0.93 (1.67)	0.63 (0.92)	0.54 (0.76)	2.27* (0.88)	1.32 (0.9)	0.53 (0.96)
Combi–floor drained/slatted	−0.47 (0.72)	1.65 (0.9)	2.00 (1.65)	0.98 (0.85)	0.5 (0.69)	1.31 (0.73)	0.94 (0.87)	2.07* (0.92)
Other/multiple flooring	0.51 (1.06)	−1.78 (1.4)	18.64 (3,445)	0.01 (1.37)	1.06 (0.93)	2.16 (1.16)	0.44 (1.46)	2.83 (1.59)

*The dependent variables are the "Being used (now or in the past)." Significance levels: < 0.05 *; < 0.01**; < 0.001***.*

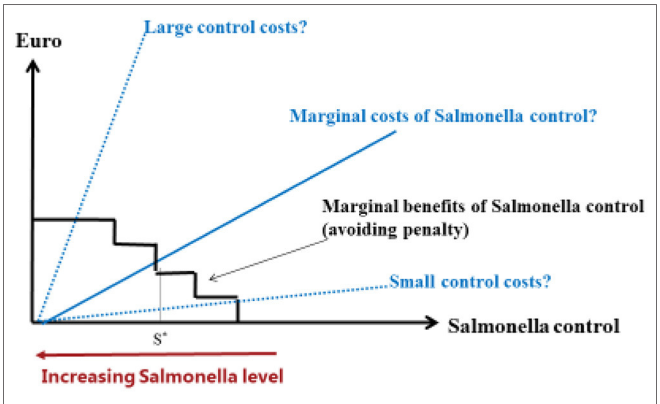


FIGURE 1 | Illustration of optimal *Salmonella* control problem with uncertainty about costs of *Salmonella* control.

GENERAL DISCUSSION

The aim of the study was to investigate whether the Danish *Salmonella* action plan — and in particular the penalty scheme — had an effect on pig farmers' efforts to control *Salmonella* in their herds. The estimated average costs and estimated benefits of *Salmonella* control together with the observation that the period in which the farmers stay in level two or three is rather short (2–3 months), leads us to conclude that the pig farmers are provided with economic incentives to implement actions aiming to reduce *Salmonella* prevalence. Further, when the farmers were asked, they expected an increase in the general prevalence of *Salmonella* if the penalty scheme were terminated (47).

This study revealed large variations between farmers regarding perceived effects and perceived costs of *Salmonella*-reducing actions. Therefore, from a policy design perspective, the approach with freedom to choose which action to implement is preferred over mandatory *Salmonella* control actions. On the other hand, the uncertainty surrounding the perceived costs and effectiveness of the individual actions places a great deal of risk on the farmers' shoulders. **Figure 1** illustrates a theoretical case with increasing marginal costs and decreasing marginal benefits of *Salmonella* control. It highlights the difficulty for a farmer to optimize *Salmonella* control when effects of actions and thereby costs of the actions are uncertain. The optimal level of *Salmonella* control is given by the intersection between the marginal benefit curve (represented by the downward sloping laddered curve) and the upward sloping marginal cost curve, which is positioned somewhere between the "small control costs" and "large control costs" curves. When the position of the marginal cost curve is uncertain, it becomes difficult to determine the optimal level of control.

Based on the heterogeneity in farmers' perceptions of costs and effects and the fact that farm characteristics vary with respect to e.g., feeding system and eligibility of section-wise production, we claim that individual herd effects are important to acknowledge when regulating a zoonosis like *Salmonella*. One of our puzzling results is that it is more likely for farmers who have not implemented a given *Salmonella* control action to believe that the action has an effect on *Salmonella*. This could indicate that farmers who have used the actions are less convinced of the effectiveness, and/or that implementation of the actions may have been driven by other motives than *Salmonella* control.

The logistic regression analysis indicated that farmers who have used a specific action were more likely to believe that this action increases productivity. This result reflects that the perceived net costs of implementing an action are lower than the running expenses (as they are adjusted for productivity gains), and hence that effect b from the theoretical model tends to be important. Direct and indirect costs of the actions (effect c from the theoretical model) tends to have a negative – but statistically insignificant – effect on farmers' propensity to implement the actions.

Due to the high uncertainty about costs and effects of the individual actions, farmers might find it optimal to use only low net cost actions and then hope this is effective enough to stay out of *Salmonella* level two or three, or even being willing to accept to have infrequent and short time periods with high prevalence. We have not addressed the important time dimension in the farmer's decision problem. However, it is likely that actions in most cases are only necessary to implement for a shorter period for the *Salmonella* level to decrease. Therefore, it is unlikely that farmers in the longer run are better off with permanent penalties compared to using reducing actions for a shorter time period. A limiting aspect of the analysis is that we have mainly included control actions that can be applied to temporary interventions to reduce *Salmonella* prevalence. A different set of questions that could address the strategic considerations of disease management in herd management will be valuable to include in a future study. The importance of veterinarians is emphasized in a report by Olsen and Christensen (47), where eight farmers out of 10 state that they base their choice of *Salmonella* control on advice from their veterinarian.

We suggest that an important task for future research is to combine studies aiming at investigating which action is most effective to lower the *Salmonella* infection level when pigs enter the abattoir with social science studies as ours investigating to what extent pig farmers have sufficient economic incentives and other motivations to control in-herd *Salmonella* prevalence. Also, valuable information could be obtained in future studies where more details about potential differences in perceptions and in *Salmonella* control practices across different types of production.

CONCLUSION

We found that Danish farmers are provided with economic incentives to reduce *Salmonella* prevalence at the herd level – as a consequence of the relation between the estimated costs (industry averages) and the estimated benefits of *Salmonella* control in terms of avoided penalties. The farmers' link a variety of costs with *Salmonella* control but it was noteworthy that variations in perceived costs could not explain the farmers' choice of *Salmonella* reducing actions. The hygiene and management related actions are not only implemented to reduce *Salmonella* prevalence in pig herds and are likely to be maintained even with a removal of the penalty scheme. On the other hand, feed and water related actions are mainly motivated by *Salmonella* reductions and are more likely to be discarded without a penalty scheme. While the incentives provided by the present action plan and in particular the penalty scheme are sound, the uncertainty about costs and effects of *Salmonella* control actions hamper the effectiveness of the penalty scheme as a regulatory tool.

DATA AVAILABILITY STATEMENT

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

AUTHOR'S NOTE

The article is based on research carried out in 2018 and 2019 by two of the authors for the Danish Ministry of Environment and Food, with the aim to evaluate the Salmonella reducing effects of an existing penalty scheme for Danish finisher pigs. The work was followed by a reference group with representatives from the Danish pig industry, The Danish Veterinary and Food Administration, Technical University of Denmark (National Veterinary Institute and National Food Institute).

AUTHOR CONTRIBUTIONS

JO and TC has contributed to conceptualization, data curation, formal analysis, validation, writing of the original manuscript, editing, and writing of the final manuscript. JD has contributed to conceptualization, formal analysis, validation, writing of the original manuscript, editing, and writing of the final manuscript. All authors contributed to the article and approved the submitted version.

FUNDING

The research design, preparation of questionnaire, analysis of data, conclusions and reporting is entirely the responsibility of the authors. The Ministry of Environment and Food provided assistance in the distribution of the questionnaire to Danish pig farmers.

ACKNOWLEDGMENTS

The authors wish to thank the reference group for the original project for commenting on preliminary drafts of the questionnaire. Also, we are thankful to two referees for valuable comments on an earlier version of the manuscript. The Ministry of Environment and Food provided assistance in the distribution of the questionnaire to Danish pig farmers.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.647697/full#supplementary-material

REFERENCES

1. EFSA and ECDC. (European Food Safety Authority, & European Centre for Disease Prevention and Control) The European Union one health 2018 zoonoses report. *EFSA J*. (2019) 17:e05926. doi: 10.2903/j.efsa.2019.5926
2. Bonardi S. *Salmonella* in the pork production chain and its impact on human health in the European Union. *Epidemiol Infection*. (2017) 145:1513–26. doi: 10.1017/S095026881700036X
3. Alban L, Stärk KDC. Where should the effort be put to reduce the *Salmonella* prevalence in the slaughtered swine carcass effectively? *Prevent Vet Med*. (2005) 68:63–79. doi: 10.1016/j.prevetmed.2005.01.001
4. Jensen JD, Belay DG. *Produktions- og Sektorøkonomiske Konsekvenser af at Reducere Antibiotikaforbruget i Dansk Svineproduktion*, IFRO Commissioned work (2019).
5. Pigou AC. *The Economics of Welfare. 4th edition*. London: Macmillan (1932).
6. EU. *Regulation no 2160/2003 of the European Parliament and of the Council of 17 November 2003 on the Control of Salmonella and Other Specified Food-Borne Zoonotic Agents*. (2003). Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32003R2160&from=EN (accessed April 4, 2021).
7. Creus E. *Swine Salmonellosis Surveillance and Control Programmes in the EU: General Basis*. (2014). Available online at: https://www.pig333.com/articles/swine-salmonellosis-surveillance-and-control-programmes-in-the-eu_8709/ (accessed April 4, 2021).
8. Danish Veterinary and Food Administration. *Salmonella og svin*. (2020). Available online at: https://www.foedevarestyrelsen.dk/Leksikon/Sider/Svinog-Salmonella.aspx (accessed April 4, 2021).
9. Baptista FM, Halasa T, Alban L, Nielsen LR. Modelling food safety and economic consequences of surveillance and control strategies for *Salmonella* in pigs and pork. *Epidemiol Infect*. (2011) 139:754–64. doi: 10.1017/S0950268810001767
10. Alban L, Baptista FM, Møgelmose V, Sørensen LL, Christensen H, Aabo S, et al. *Salmonella* surveillance and control for finisher pigs and pork in Denmark — a case study. *Food Res Int*. (2012) 45:656–65. doi: 10.1016/j.foodres.2011.02.050
11. Goldbach SG, Alban L. A cost–benefit analysis of Salmonella-control strategies in Danish pork production. *Preventive Veterinary Medicine*. (2006) 77:1–14. doi: 10.1016/j.prevetmed.2005.10.008
12. 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
13. Botteldoorn N, Heyndrickx M, Rijpens N, Grijspeerdt K, Herman L. *Salmonella* on pig carcasses: positive pigs and cross contamination in the slaughterhouse. *J Appl Microbiol*. (2003) 95:891–903. doi: 10.1046/j.1365-2672.2003.02042.x
14. Baptista FM, Dahl J, Nielsen LR. Factors influencing *Salmonella* carcass prevalence in Danish pig abattoirs. *Prevent Vet Med*. (2010) 95:231–8. doi: 10.1016/j.prevetmed.2010.04.007
15. Rostagno MH, Callaway TR. Pre-harvest risk factors for *Salmonella* enterica in pork production. *Food Res Int*. (2012) 45:634–40. doi: 10.1016/j.foodres.2011.04.041
16. Danish Veterinary and Food Administration. *Salmonella Handlingsplan for Svin SH5*. (2013). Available online at: https://www.foedevarestyrelsen.dk/SiteCollectionDocuments/25_PDF_word_filer%20til%20download/04kontor/Mikro%20zoonose/Salmonellahandlingsplan%20svin%20SH5.pdf (accessed April 4, 2021).

17. Ministry of Environment and Food of Denmark. *Executive Order 1792 from December 2, 2020*. Bekendtgørelse om salmonella hos svin (2020).
18. SEGES. *Vejledning til Svineproducenter om Salmonella. Pig Research Centre, Danish Agriculture and Food Council*. (2021). Available online at: https://svineproduktion.dk/-/media/PDF/Pjecer/Vejledning-til-svineproducenter-om-Salmonella.ashx (accessed April 4, 2021).
19. Ministry of Environment and Food of Denmark. *Guide 9697 from August 7, 2017*. Vejledning til bekendtgørelse om salmonella hos svin (2017).
20. Simon-Grife M, Martín-Valls GE, Vilar MJ, García-Bocanegra I, Martín M, Mateu E, et al. Biosecurity practices in Spanish pig herds: perceptions of farmers and veterinarians of the most important biosecurity measures. *Prevent Vet Med.* (2013) 110:223–31. doi: 10.1016/j.prevetmed.2012.11.028
21. Gotter V, Klein G, Koesters S, Kreienbrock L, Blaha T, Campe A. Main risk factors for *Salmonella*-infections in pigs in north-western Germany. *Prevent Vet Med.* (2012) 106:301–7. doi: 10.1016/j.prevetmed.2012.03.016
22. Wilhelm B, Rajić A., Parker S, Waddell L, Sanchez J, Fazil A, et al. Assessment of the efficacy and quality of evidence for five on-farm interventions for Salmonella reduction in grow-finish swine: a systematic review and meta-analysis. *Prevent Vet Med.* (2012) 107:1–20. doi: 10.1016/j.prevetmed.2012.07.011
23. Bjork KE, Fields V, Garber LP, Kopral CA. Factors associated with *Salmonella* prevalence in U.S. Swine grower–finisher operations. *Foodborne Pathog Dis.* (2018) 15:489–97. doi: 10.1089/fpd.2017.2364
24. Jørgensen L, Dahl J, Wingstrand A. The effect of feeding pellets, meal and heat treatment on the *Salmonella* prevalence in finishing pigs. In: *Proceedings of the 2nd International Symposium on the Epidemiology and Control of Salmonella.* Pork, WA (1999) doi: 10.31274/safepork-180809-1034
25. Kjeldsen N, Dahl J. The effect of feeding non-heat treated, non-pelleted feed compared to feeding pelleted, heat-treated feed on the *Salmonella*-prevalence of finishing pigs. In: *Proceedings of the 2nd International Symposium on the Epidemiology and Control of Salmonella.* Pork, WA (1999). doi: 10.31274/safepork-180809-1035
26. Jørgensen L, Kjaersgaard H, Wachmann H, Jensen B, Knudsen K. Effect of wheat bran and wheat:barley ratio in pelleted feed on *Salmonella* prevalence and productivity of finishers. In: *Proceedings of the 4th International Symposium on the Epidemiology and Control of Salmonella and Other Foodborne Pathogens*. Pork (2001). doi: 10.31274/safepork-180809-209
27. Jørgensen L, Boes J, Kranker S, Kjaersgaard H, Wachmann H. Effect of an optimised pelleted diet on Salmonella prevalence and pig productivity. In: Fifth *International Symposium on the Epidemiology and Control of Foodborne Pathogens in Pork*. Crete (2003). doi: 10.31274/safepork-180809-480
28. Lucia ADD, Ostanello F. On-farm risk factors associated with *Salmonella* in pig herds. *Large Animal Rev.* (2020) 26:133–40. Available online at: https://www.largeanimalreview.com/index.php/lar/article/view/124/79
29. Creus E, Pérez JF, Peralta B, Baucells F, Mateu E. Effect of acidified feed on the prevalence of *Salmonella* in market-age pigs. *Zoonoses Pub Health.* (2007) 54:314–9. doi: 10.1111/j.1863-2378.2007.01069.x
30. Andres VM, Davies RH. Biosecurity measures to control *Salmonella* and other infectious agents in pig farms: a review. *Comprehen Rev Food Sci Food Safety.* (2015) 14:317–35. doi: 10.1111/1541-4337.12137
31. Farzan A, Friendship RM, Dewey CE, Warriner K, Poppe C, Klotins K. Prevalence of *Salmonella* spp. on Canadian pig farms using liquid or dry-feeding. *Prevent Vet Med.* (2006) 73:241–54. doi: 10.1016/j.prevetmed.2005.09.003
32. van der Heijden M, Dam, Niewerth HVD, Frankena K. Effectiveness of *Salmonella* control strategies in fattening pigs. In: Sixth *International Symposium on the Epidemiology and Control of Foodborne Pathogens in Pork*. Rohnert Park, CA (2005). doi: 10.31274/safepork-180809-736
33. Schmidt PL, O'Connor AM, McKean JD, Hurd HS. The association between cleaning and disinfection of lairage pens and the prevalence of *Salmonella* enterica in swine at harvest. *J Food Protect.* (2004) 67:1384–8. doi: 10.4315/0362-028X-67.7.1384
34. Leirs H, Lodal J, Knorr M. Factors correlated with the presence of rodents on outdoor pig farms in Denmark and suggestions for management strategies. *NJAS Wageningen J Life Sci.* (2004) 52:145–61. doi: 10.1016/S1573-5214(04)80010-1
35. Alarcon P, Wieland B, Mateus A, Dewberry C. Pig farmers' perceptions, attitudes, influences and management of information in the decision-making process for disease control. *Prevent Vet Med.* (2014) 116:223–42. doi: 10.1016/j.prevetmed.2013.08.004
36. Marier E, Piers Smith R, Ellis-Iversen J, Watson E, Armstrong D, Hogeveen H, et al. Changes in perceptions and motivators that influence the implementation of on-farm *Salmonella* control measures by pig farmers in England. *Prevent Vet Med.* (2016) 133:22–30. doi: 10.1016/j.prevetmed.2016.09.009
37. Lund M, Gülec Ö. *Kvæg- og Svineproducenters Holdninger til Smittebeskyttelse og Smittebeskyttelsesplaner*. IFRO Commission Work 2013/16. Department of Food and Resource Economics, University of Copenhagen. (2013). Available online at: https://static-curis.ku.dk/portal/files/95167529/IFRO_Udredning_2013_16.pdf (accessed April 4, 2021). [In Danish].
38. Danish Veterinary and Food Administration. *The Central Husbandry Register (CHR)*. Ministry of Environment and Food, Danish Veterinary and Food Administration. (2019). Available online at: https://www.foedevarestyrelsen.dk/english/Animal/AnimalHealth/Central_Husbandry_Register/Pages/default.aspx [In Danish].
39. Danish Veterinary and Food Administration. *The Zoonosis Register*. Ministry of Environment and Food, Danish Veterinary and Food Administration (2019). Available online at: https://zoor.fvst.dk/zoor/faces/home?_adf.ctrl-state=41xjcq3vy_3
40. Sloth NM, Tybirk P, Dahl J, Christensen G. *Effekt af Formalingsgrad og Varmebehandling/Pelletering på Mavesundhed, Salmonella-Forebyggelse og Produktionsresultater hos Slagtesvin*. Danish Pig Research Centre (1998).
41. Hansen CF, Dahl J, Jørgensen L. *Effekt af Myresyre i Drikkevand på Forekomst af Salmonella hos Slagtesvin*. Danish Pig Research Centre (1999).
42. Busch ME, Jensen T. *Smitteafbrydelse og produktivitet i slagtesvinehold i multisite-systemer. Meddelelse Nr. 708: Landsudvalget for Svin, Videncenter for Svineproduktion, Den Rullende Afprøvning*. (2005). Available online at: https://svineproduktion.dk/publikationer/kilder/lu_medd/2005/708 (accessed April 4, 2021).
43. Pedersen AØ, Canibe N. *Fermentering af Korn Giver en Lille Stigning i Energiværdien*. Danish Pig Research Centre (2011).
44. Jørgensen T. *Personal communication*, Copenhagen, (2019).
45. Statistics Denmark. *Priser for Jordbrugets Produktionsfaktorer Efter Produkt og Enhed.* (2019). Available online at: https://www.statistikbanken.dk/LPRIS35.
46. SEGES. *Få et Overblik Over Landbrugets Indtjening*. Landbrugsinfo, Økonomi og ledelse. (2018). Available online at: https://www.landbrugsinfo.dk/oekonomi/oekonomiske-analyser/driftsresultater-priser-prognoser/sider/startside.aspx (accessed April 4, 2021).
47. Olsen JV, Christensen T. Analyse af effekten af det økonomiske incitament i bodssystemet i salmonellahandlingsplanen for svin, 81 s. Copenhagen: Department of Food and Resource Economics (IFRO) Commissioned work 2019/13 (2019).

Conflict of Interest: JO and TC collaborate with employees from the Danish pig industry in a separate project with no links to the project here reported.

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

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 24 May 2021
doi: 10.3389/fvets.2021.646458

Engaging Stakeholders in the Design of One Health Surveillance Systems: A Participatory Approach

Marion Bordier[1,2]*, *Flavie Luce Goutard*[1,3,4], *Nicolas Antoine-Moussiaux*[5], *Phuc Pham-Duc*[6,7], *Renaud Lailler*[8,9] *and Aurelie Binot*[1,2]

[1] ASTRE, Univ Montpellier, CIRAD, INRAE, Montpellier, France, [2] CIRAD, UMR ASTRE, Montpellier, France, [3] Faculty of Veterinary Medicine, Kasetsart University, Bangkok, Thailand, [4] CIRAD, UMR ASTRE, Bangkok, Thailand, [5] Fundamental and Applied Research for Animals and Health Research Unit, Faculty of Veterinary Medicine, University of Liege, Liege, Belgium, [6] Center for Public Health and Ecosystem Research, Hanoi University of Public Health, Hanoi, Vietnam, [7] Institute of Environmental Health and Sustainable Development (IEHSD), Hanoi, Vietnam, [8] Laboratoire de Sécurité des Aliments, Agence Nationale de Sécurité Sanitaire de l'Alimentation, de l'Environnement et du Travail (ANSES), Maisons-Alfort, France, [9] Université Paris-Est Créteil Val de Marne, Créteil, France

OPEN ACCESS

Edited by:
Bouda Vosough Ahmadi,
European Commission for the Control of Foot and Mouth Disease (EuFMD), Italy

Reviewed by:
Anna Sophie Fahrion,
Friedrich Loeffler Institute, Germany
Monique Sarah Léchenne,
Swiss Tropical and Public Health Institute (Swiss TPH), Switzerland

***Correspondence:**
Marion Bordier
marion.bordier@cirad.fr

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: 26 December 2020
Accepted: 02 March 2021
Published: 24 May 2021

Citation:
Bordier M, Goutard FL, Antoine-Moussiaux N, Pham-Duc P, Lailler R and Binot A (2021) Engaging Stakeholders in the Design of One Health Surveillance Systems: A Participatory Approach. Front. Vet. Sci. 8:646458. doi: 10.3389/fvets.2021.646458

Many One Health surveillance systems have proven difficult to enforce and sustain, mainly because of the difficulty of implementing and upholding collaborative efforts for surveillance activities across stakeholders with different values, cultures and interests. We hypothesize that only the early engagement of stakeholders in the development of a One Health surveillance system can create an environment conducive to the emergence of collaborative solutions that are acceptable, accepted and therefore implemented in sustainable manner. To this end, we have designed a socio-technical framework to help stakeholders develop a common vision of their desired surveillance system and to forge the innovation pathway toward it. We implemented the framework in two case studies: the surveillance of antimicrobial resistance in Vietnam and that of *Salmonella* in France. The socio-technical framework is a participatory and iterative process that consists of four distinct steps implemented during a workshop series: (i) definition of the problem to be addressed, (ii) co-construction of a common representation of the current system, (iii) co-construction of the desired surveillance system, (iv) identification of changes and actions required to progress from the current situation to the desired situation. In both case studies, the process allowed surveillance stakeholders with different professional cultures and expectations regarding One Health surveillance to gain mutual understanding and to reconcile their different perspectives to design the pathway toward their common vision of a desired surveillance system. While the proposed framework is structured around four essential steps, its application can be tailored to the context. Workshop facilitation and representativeness of participants are key for the success of the process. While our approach lays the foundation for the further implementation of the desired One Health surveillance system, it provides no guarantee that the proposed actions will actually be implemented and bring about the required changes. The engagement of stakeholders in a participatory process must be sustained in order to ensure the implementation of co-constructed solutions and evaluate their effectiveness and impacts.

Keywords: antimicrobial resistance, co-construction, One Health, participatory, *Salmonella*, surveillance

INTRODUCTION

The One Health concept calls for systemic approaches to better understand and manage complex health problems. This requires the bridging of activities carried out in the human, animal, and environmental health sectors, mobilizing the different professions and decision-making scales, and establishing interdisciplinary approaches that bring together biomedical, environmental, and social sciences (1).

International organizations, governments, and the scientific community are widely promoted the application of the One Health concept to surveillance when it deals with complex health hazards such as zoonotic diseases, antibiotic resistance, or biological and chemical contaminants in the food chain (2, 3). The approach highlights potential improvements of surveillance in terms of epidemiological and economic performance. Ultimately, it is expected to improve knowledge of health events and their management, while reducing the costs associated with surveillance activities and interventions (4–6). However, a wide range of technical, organizational, and sociological factors is impeding the sustainable implementation of One Health surveillance (7–12).

Surveillance mobilizes networks of stakeholders with specific roles and missions subject to their own constraints. It produces information for different categories of beneficiaries with different expectations (13). Although surveillance is most often associated with positive impacts (improvement of the prevention and management of health events), it can have negative repercussions for certain stakeholders (destruction of food products following the detection of health hazards, slaughtering of animals following the detection of certain diseases). This diversity of values, cultures, and interests that coexist within a surveillance system is even more prevalent in a One Health surveillance system where the variety of stakeholders is broader (14). This results in the coexistence of a multiple of representations of the current surveillance system and of changes to improve it, which restrains collective action toward the implementation of One Health surveillance (15, 16). We hypothesize that the collective construction of a common representation of the desired One Health surveillance system is likely to foster mutual understanding among stakeholders and to let emerge collective solutions to operationalize collaboration (17). In addition, the early involvement of stakeholders in collective decision-making should improve their adherence to the proposed solutions and thus their commitment to implementation (18, 19).

To this end, we have developed a socio-technical framework to help stakeholders to construct a common vision of their desired One Health surveillance system and to identify the solutions to make it operational. The framework is an actor-based process, composed of several participatory tools, and implemented during a series of workshops with representatives of surveillance stakeholders. It guides participants in the definition of the causal links between their vision and the changes and actions required to achieve it, so they progressively build the innovation pathway that lays the foundations for the further implementation of the One Health surveillance system. We applied this participatory process to two case studies, the surveillance of antimicrobial resistance (AMR) in Vietnam and the surveillance of *Salmonella* in France. In Vietnam, the government has promulgated a national strategy to combat antimicrobial resistance, including provisions for the establishment of an integrated surveillance system including surveillance activities in the animal health, human health, and environmental sectors (7). Within this context, we offered to support the surveillance stakeholders in defining how the multi-sectoral system would be organized and operate in response to the governmental inquiry. In France, a technical work group, consisting of public and private partners, has been established to optimize the surveillance of *Salmonella* through a better coordination of surveillance activities in the different sectors and at all stages of the food chain (20). We guided the work group in their collective reflection to define their desired surveillance system and the changes needed to establish it.

MATERIALS AND METHODS

We have developed and applied a socio-technical framework, which is intended to be implemented during a series of workshops. It consists of four steps: (i) definition of the problem to be addressed based on participant expectations, (ii) co-construction of a common representation of the system in place, (iii) co-construction of the desired surveillance system, (iv) identification of changes and actions required to progress from the current situation to the desired situation and construction of the innovation pathway (**Figure 1**). This framework is implemented using various participatory tools, which can be applied differently depending on the context of implementation and on the information gathered during the process. The description of the case studies illustrates its application to two different epidemiological and socio-political contexts.

Below, we first explain how the workshops were organized and then explain, in detail, the four steps of the framework and how we applied it to the two case studies, using different participatory tools (**Table 1**).

Organization of the Workshop Series

The four steps of the socio-technical framework were implemented during three half-day workshops for each case study.

The selection of workshop participants was crucial because their representativeness would determine the richness and relevance of the results produced. As the objective of the process was to gain a fully comprehensive vision of the surveillance systems, it was necessary for all surveillance functions to be represented among participants, while avoiding an over-representation of any one category of stakeholders. In the case of Vietnam, potential participants were identified based on the results of a previous stakeholder analysis study (7). All categories of stakeholders operating in or influencing the system were considered and invited (**Table 2**). In France, no new recruitment was required as the participants were actually the members of the technical work group (**Table 3**).

Before starting discussions, all participants were informed about the organization of the full process.

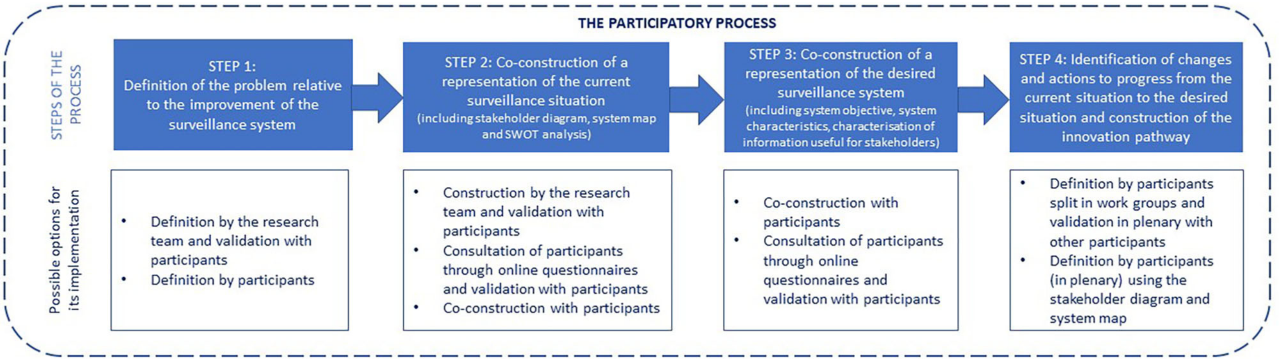


FIGURE 1 | The socio-technical framework structure and its application modalities.

TABLE 1 | Description of the process implementation in Vietnam (surveillance of antimicrobial) and in France (surveillance of *Salmonella*).

	Steps of the socio-technical framework			
	Step 1: Definition of the problem to address	**Step 2: Co-construction of the representation of the current situation of the surveillance system**	**Step 3: Definition of the desired surveillance system**	**Step 4: Definition of changes and actions required to achieve the desired surveillance system**
Surveillance of AMR in Vietnam	Validation of the problem with participants (plenary discussion) (WS 1)	Building the stakeholder diagram and system map using information shared by participants (plenary discussion using cards) (WS 1) SWOT implementation (plenary discussion) (WS 1)	Definition of the objective of the desired surveillance system and of its core characteristics (plenary discussion) (WS 2)	Identification of changes and actions during plenary discussion (WS 2) and then during group work followed by validation in plenary (WS 3)
Surveillance of *Salmonella* in France	Definition of the problem with participants (plenary discussion using cards) (WS1)	Refining the stakeholder diagram and system map (designed by the research team) with information shared by participants (plenary discussion) (WS 1) Characterization of the desired surveillance system applying thematic analysis to expectations shared by participants (plenary discussion using cards) (WS 1) SWOT implementation (on-line questionnaire)	Characterization of the desired surveillance system using thematic analysis on participants' expectations (WS 1) and characterization of the useful information (group work followed by validation in plenary) (WS 2)	Identification of changes and actions during group work (WS 2 and 3) and followed by validation in plenary (WS 3)

WS, workshop.

The workshops were facilitated by pairs of researchers, selected for their ability to lead discussion groups and handle participatory tools and for their legitimacy, in the eyes of the participants, in dealing with the subjects discussed. The choice of facilitators is an important element that influences the success of the participatory process. The facilitators ensured that each participant had the opportunity to express his/her opinion. They encouraged participants to clarify their ideas when too generic or subject to confusion, rewording them when necessary, and obtained general approval from the audience. In Vietnam, facilitation was provided by a researcher who had participated in the development of the methodological framework and had a good knowledge of the system and its stakeholders, and by an academic who is used to facilitating group discussions on cross-cutting health issues. In France, both facilitators had participated in the development of the framework. One had a good knowledge of the system in place; the other had a strong experience in the application of participatory tools and systemic approaches.

For each workshop organized, two observers were designated. Their role was to record the discussions among participants and with the facilitator by taking handwritten notes and pictures.

At the beginning of each workshop, the results of the previous workshop were presented so that participants could reflect on previous work, provide comments, make changes or clarify points, if necessary.

First Step: Definition of the Problem to Address

The reason behind the willingness to implement a One Health surveillance system varies depending on the context and may be perceived differently by participants. In this first step, therefore, we helped participants to express the problem to be addressed

TABLE 2 | Description of the stakeholders invited and participating in the participatory process in Vietnam.

Sector	Professional category	Invited	Participating		
			First workshop	Second workshop	Third workshop
Multi-sectoral	Authorities (national level)	1	0	1	3
Animal health	Authorities (national level)	3	2	0	0
	National research institutes	1	1	2	2
	International research or technical institutes	1	0	0	1
	International organizations	1	1	4	1
	Pharmaceutical and feed companies	2	1	2	1
Human health	Authorities (national level)	2	1	0	1
	National research institutes	1	0	0	1
	Practitioners (hospitals)	2	0	0	1
	International research or technical institutes	2	3	1	2
	International organizations	1	0	0	1
Food safety	Authorities (national level)	1	1	1	1
	National research institutes	1	0	0	0
Environment	Authorities (national level)	1	0	0	0
	Total	20	10	11	15

TABLE 3 | Description of the stakeholders invited and participating in the participatory process in France.

Sector	Professional category	Participating		
		First workshop	Second workshop	Third workshop
Animal health	Scientific or technical institutes	6	2	5
	Professional organizations	4	4	4
Food safety	Authorities	2	2	2
	Scientific or technical institutes	3	3	2
	Professional organizations	7	4	5
Feed safety	Authorities	1	0	0
	Scientific or technical institutes	1	1	1
	Professional organizations	3	2	3
	Total*	21	15	18

Participants may belong to several categories.

in terms of improvement of the current surveillance situation. The objective was to obtain a clear formulation of the problem in terms that everyone could understand and that reflected a common interest for the process. This step was also intended to strengthen participants' commitment to the process by clearly explaining the problem they wished to address through their participation in the workshops. In Vietnam, an inter-ministerial strategy to combat AMR had called for the establishment a multi-sectoral surveillance system and surveillance stakeholders had expressed the need for a multi-stakeholder platform where they could discuss the most appropriate collaborative modalities to implement (7). The issue was therefore predefined but required clarification at the beginning of the first workshop to ensure consensus on the scope of the process and the terminology used. In France, the implementation of the framework was part of the technical group's work plan, but it was necessary to clearly redefine the expectations of each participant engaged in the process in order to collectively formulate a question that obtained full consensus. At the beginning of the first workshop, all participants were asked to write on cards their expectations regarding their involvement in the process. An analysis and thematic codification of expectations were carried out as they were formulated by participants in order to obtain a single, concerted question (**Figure 2**).

Second Step: Co-construction of the Representation of the Current Situation of the Surveillance System

The representation of the current situation was determined by describing the current organization and functioning of the surveillance system through three outputs: a diagram of stakeholder interaction within the system (stakeholder diagram), a description of the surveillance programs that are part of the system (system map), and an analysis of the strengths, weaknesses, opportunities, and threats (SWOT) of the system within the context of shift toward One Health surveillance.

Stakeholder Diagram

The method used to build the stakeholder diagram was inspired from the PARDI (Problem, Actors, Dynamics, Resources, Interactions) method. It was developed by the ComMod[1] community to help stakeholders to conceptualize the system surrounding the problem they wish to address and to find solutions to solve the problem (21). It leads to the emergence of a shared representation of the system, integrating the respective knowledge, point of view and expertise of all the participants (22). The process is also an opportunity for participants to learn

[1]https://www.commod.org/en/qui-sommes-nous/association.

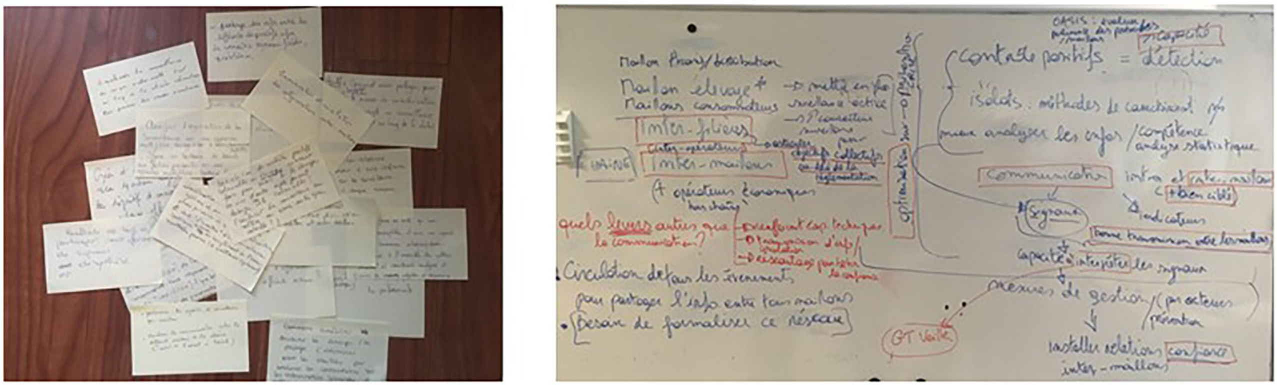


FIGURE 2 | Expectations individually expressed by participants **(left)** and thematic analysis and coding to define the common problem to address **(right)** during the workshops in France.

from each other and to generate new knowledge, allowing for the development of mutual understanding (23).

In our framework, we applied the PARDI tool to obtain a stakeholder diagram representing all the stakeholders involved in or impacted by the surveillance system, identifying their roles and missions in relation to surveillance and characterizing the interactions between them. This type of diagram can be developed in different ways. In Vietnam, the entire diagram was co-constructed by combining, in a concerted manner, the information given by the participants during the first collective workshop. Using cards and white boards, facilitators gathered information on main surveillance stakeholders, interactions between them, and their role and responsibilities in the surveillance system (**Figure 3**). In France, a draft stakeholder diagram focusing on information flows was drawn up by the facilitators on the basis of available information and then submitted for amendment and validation to the participants of the first workshop. The diagram was projected on a white board and participants were invited to bring necessary changes using markers (**Figure 4**).

System Map

Once the stakeholder diagram was complete, stakeholders interacting in the same surveillance program were grouped together to clearly identify the stakeholder network specific to each program. The need to move from an actor-centered to a program-centered representation emerged during the course of the study to highlight collaboration existing between surveillance programs for the governance and/or the implementation of integrated surveillance activities, those collaboration being at the heart of One Health surveillance. For the two case studies, the system map was constructed by the facilitators on the basis of the information collected during the first workshop and then validated during the second workshop with the participants.

Identification of the Strengths, Weaknesses, Opportunities, and Threats (SWOT) for the Current Surveillance System

Participants were then asked to conduct a SWOT analysis, i.e., to identify the strengths (S) and weaknesses (W), both internal to the current system as well as existing external threats (T) and unexploited opportunities (O) relative to a shift toward a more effective system (24). Weaknesses and threats are, respectively, the internal and external obstacles that must be addressed to improve the surveillance system; strengths and opportunities are elements that can be used to remove these obstacles. In this participatory process, the SWOT analysis is used as snapshot of the current situation to trigger participant reflection on the need for surveillance improvement. In Vietnam, this work was conducted at the end of the first workshop, by asking participants to propose strengths, weaknesses, opportunities, and threats in turn. The thematic coding progress was done *a posteriori* by the research team. In France, this work was carried out through a questionnaire sent to the participants, with the grouping of results presented at the second workshop.

Third and Fourth Steps: Definition of the Desired Surveillance System and Necessary Changes

Once participants had agreed on a common representation of the surveillance system, the next step was for them to define their desired surveillance system and build the pathway to reach it. During these two stages, the methodology used in the participatory process referred to the ImpresS method developed by Cirad (the French Agricultural Research Center for International Development) to better consider the impact when constructing a research intervention. It is a participatory, iterative and adaptive process enabling stakeholders to formulate a common vision based on the desired and most convincing impact pathway that the innovation process should follow (25, 26). The impact pathway is a tool grounded in the theory-driven evaluation literature (27). It represents and makes explicit the causal links between the inputs (resources used by the research team), the outputs of the research activities (knowledge, training, technology, etc.), outcomes (e.g., appropriation of the outputs by people), and impacts. We mobilized this framework to define the causal links between actions and changes proposed by participants and their vision of the desired surveillance system (characteristics and objective).

FIGURE 3 | Identification of surveillance stakeholders **(left)** and of interactions between them **(middle)** together with their role and responsibilities **(right)** in the surveillance system of antimicrobial resistance in Vietnam.

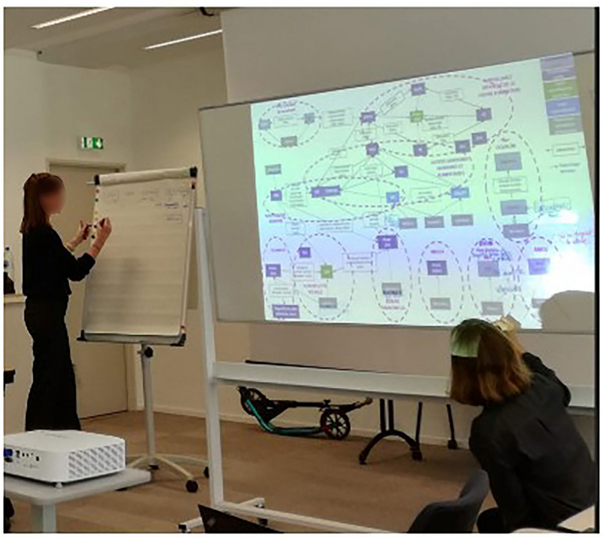


FIGURE 4 | Revision of the stakeholder diagram with the participants of the first workshop in France.

Definition of the Desired Surveillance System

In Vietnam, the approach was to lead the workshop participants to define a concerted objective for an optimal multi-sectoral AMR surveillance system. To this end, an open discussion with the whole group was initiated to encourage participants to develop their views on the most relevant objective and purpose for the system in the mid-term (3–5 years). Their different proposals were discussed with the aim of agreeing upon a common objective, reflecting the views of the different participants. On this basis, the system characteristics required to meet this objective were identified.

In France, the desired system was first defined according to the expectations expressed by participants during the first workshop during which they defined the problem to address. As the latter focused on the circulation of useful information, in a second step, the participants further characterized the information they deemed useful for their activities. To this end, the participants were divided into three homogeneous groups according to their main professional category (competent authorities, research and technical institutes, professional organizations) and were asked to identify up to five types of information that they considered useful for *Salmonella* risk management within the context of their mission. They then qualified the information according to type, format required, existence/location, accessibility, use, and valorization.

Definition of Changes and Actions Required to Achieve the Desired Surveillance System

During this last step, participants reflected on all the information produced in the previous steps to identify changes and actions required for the operationalization of their vision of the desired surveillance system. By articulating these changes and actions with the representation of the desired surveillance system, we obtained a graphical representation of the stakeholders' theory of change.

In Vietnam, participants were first questioned, in the light of the SWOT analysis results, about the changes to be brought to the current surveillance system to meet the previously defined objectives and characteristics. The changes could target a reorganization of surveillance activities in terms of governance and implementation (addition or removal of a stakeholder; revision, addition or removal of an interaction or action), changes in stakeholder posture, capacity and resources, or any other type of changes relevant to them. Changes proposed by participants, once validated by the entire audience, were directly reported on the stakeholder diagram co-constructed in the second step that was projected on a white board. Then, participants were divided into two homogeneous groups, one consisting of people working in the human health sector and the other of people working in the animal health and food safety sectors. They were asked to rank identified changes according to priority and to propose concrete actions to implement the most important. The results of each group were then presented, discussed, and amended by the other participants.

In France, participants were asked to identify the changes they considered necessary to ensure that useful information could flow properly. To do this, participants split up into groups of three to four people and brainstormed on three changes to be implemented as a priority to promote the flow of useful information. To feed their reflections, they referred to the outputs produced in the previous steps (representation of the desired system, mapping of useful information, SWOT results). The proposed changes could be general -relative to the system— or concern a specific stakeholder. They could be of different types: changes in practices (e.g., actions that stakeholders should do differently), changes in knowledge/capacity (e.g., type of knowledge or capacity the stakeholders should acquire), changes in posture (e.g., type of perception and motivation required by the stakeholders), changes in interaction (e.g., type of interactions the stakeholders should develop). The changes identified were then shared and a thematic analysis was carried out with the whole group to identify, in a concerted manner, the major changes to be implemented in order to reach the desired system.

Figure 1 summarizes possible modalities to apply the socio-technical framework in the different steps.

RESULTS

Surveillance of AMR in Vietnam

In Vietnam, the participatory process was implemented during three half-day workshops between December 2018 and January 2019. The participants were from the human health, animal health and food safety sectors. Their number varied between workshops as described in **Table 2**. For the majority of institutions, only one representative attended the workshops. Two institutions withdrew from the process after the first workshop because they considered that their activity was not directly related to AMR surveillance (environmental authorities) or because they had delegated their surveillance mission to a third party (animal health authorities).

Definition of the Problem

During the first workshop, participants agreed on the boundaries of the AMR surveillance system that would be the subject of their discussion. They decided to concentrate on resistance to antibiotics only, while the organization and functioning of the surveillance of antibiotic use would not be addressed. In addition, research and epidemiological surveys would not be considered as surveillance programs unless repeated over time.

Representation of the Current Surveillance System

Stakeholder Diagram and System Map

The stakeholder diagram was developed collectively during the first workshop and revised at the beginning of the second workshop (**Figure 5**).

In Vietnam, the authorities have initiated three surveillance programs: clinical isolates in hospitals, commensal and zoonotic bacteria in animal commodities, and commensal and zoonotic bacteria in healthy animals. The most accomplished surveillance system is that of human clinical isolates, which is deployed in a network of 16 central and regional hospitals and has long received technical and financial support from foreign research institutes. Surveillance in food or in animals is managed by a lead institution—either a national research institution or a public laboratory—which carries out most of the tasks (coordination, collection and laboratory analysis, data analysis and interpretation, scientific and technical support). Conversely, surveillance in hospitals is much less centralized and involves a wide variety of stakeholders. The local authorities are not involved in any surveillance networks other than for retail food. The authorities in charge of the surveillance programs in the different domains—food-producing animals, retail food, and hospital patients—operate in silos with a lack of coordination. Governmental institutions involved in AMR surveillance are also poorly connected within the same sector.

Simultaneously, the pharmaceutical industry conducts pre-marketing resistance surveillance programs for antibiotics in hospitals and among the population. The organization of these surveillance programs varies from one area to another.

The stakeholder diagram was then used to produce the system map (**Figure 6**). This figure underlined that certain surveillance programs were covering the same domains and yet did not collaborate. The only existing collaboration among different programs was the joint use of surveillance results from hospitals and in animals during the public awareness week, under the impulsion of international organizations.

Surveillance System SWOT Analysis Results

The system's greatest strength resides in the presence of all the necessary structural elements at the surveillance program level to enable a functional multi-sectoral surveillance system (designated coordination units, functional laboratory network, etc.). The system also benefits from a strong political will, on behalf of national authorities and intergovernmental organizations, to combat AMR. Additionally, Vietnam has a culture and strong inter-institutional collaborative experience in the control of zoonotic diseases (rabies, avian influenza in particular) that can serve as a framework for the governance of the multi-sectoral AMR surveillance system. The surveillance programs show shortcomings in terms of governance (weak involvement of local authorities and insufficient resources) and operations (poor quality and unrepresentative data, too lengthy a reception time for laboratory results). At the system level, participants highlighted weaknesses in governance (steering, coordination, and scientific and technical support). The system also faces a number of challenges: the large number of stakeholders to be coordinated, the diverse format of data collected, the absence of government funding, the lack of involvement of certain governmental organizations and the lack of effective dissemination of surveillance results to decision-makers.

Desired Multi-Sectoral Surveillance System

The participants agreed that the priority was to produce relevant information within each sector and for each category of stakeholders in order to properly inform their decision and evaluate the effectiveness of the management measures implemented. Therefore, the participants defined the ideal surveillance system as a system capable of monitoring trends over time and space in all relevant domains, in order to improve general knowledge, inform sectoral risk assessment studies (including the correlation between use and resistance), support the development and evaluation of interventions in each sector and identify research needs. For such a system to be

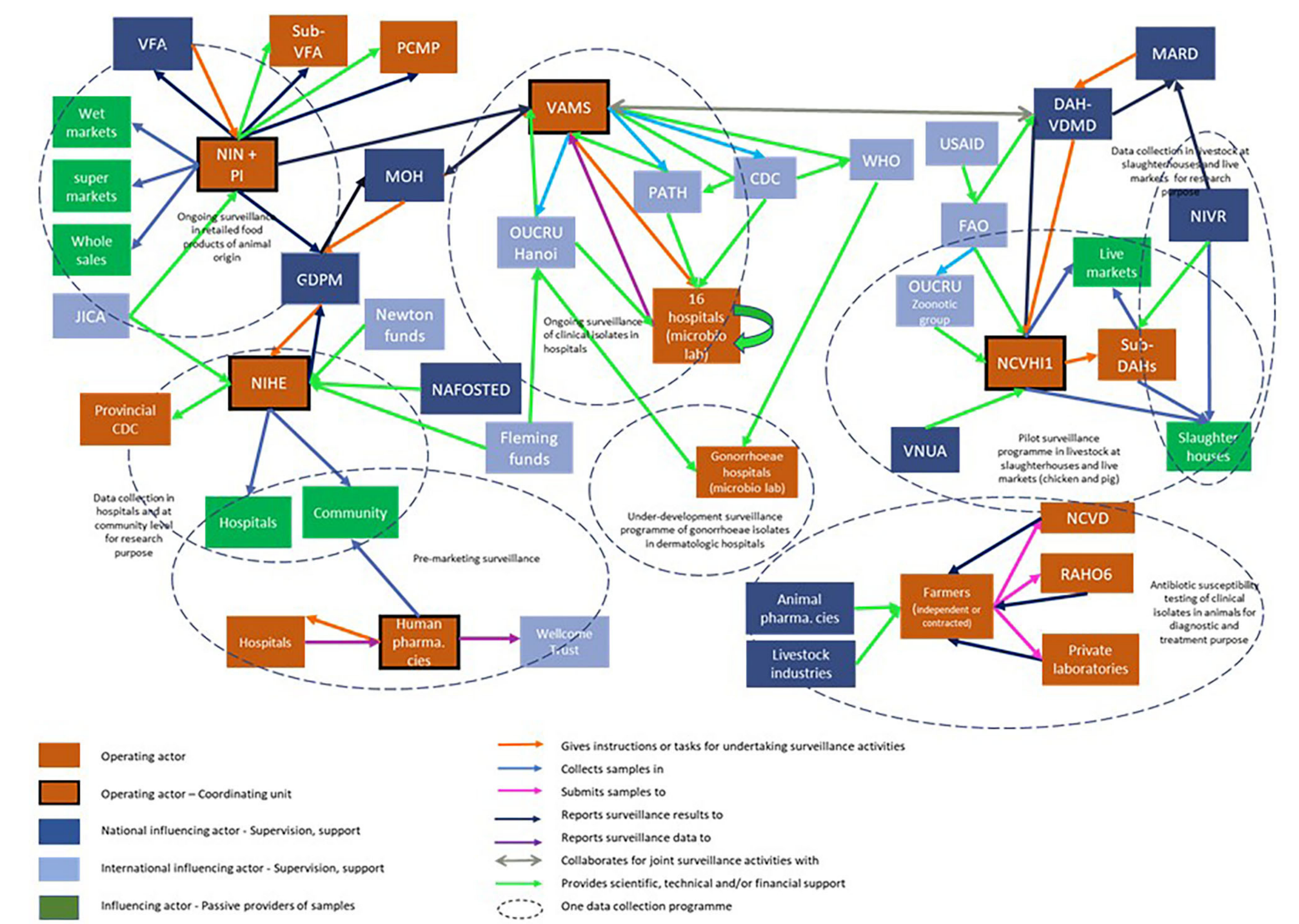


FIGURE 5 | Stakeholder diagram for the surveillance system of antimicrobial resistance in Vietnam. CDC, center for disease control; DAH, department of animal health; FAO, Food and agriculture organization; GDPM, General department of preventive medicine; JICA, Japanese international cooperation agency; MARD, Ministry of agriculture and rural development; MOH, Ministry of Health; NAFOSTED, National Foundation for Science and Technology Development; NCVD, National center for veterinary diseases; NIHE, National institute of hygiene and disease control and prevention; VAMS, Vietnam administration of medical services; VFA, Vietnam food administration; VNUA, Vietnam National University of Agriculture; NCVHI1, National center for veterinary hygiene 1; NIN, National institute of nutrition; NIVR, National institute of veterinary research; WHO, World health organization; OUCRU, Oxford University Clinical Research Unit; PATH-CDC, PATH program of the United States Center for disease control and prevention; PI, Pasteur institutes; RAHO6, Regional animal health organization 6; USAID, United States agency for international development; US-CDC, United Stator Center for disease control.

functional and sustainable, four conditions were identified: the system had to cover all relevant domains, surveillance had to be effective and sustainable in all domains, surveillance results had to be used to inform decision making, the different institutions in charge of coordinating surveillance had to share results and any other relevant information (**Figure 7**).

Necessary Changes to Achieve the Desired Surveillance System

Based on all the information produced during the previous steps, participants proposed different changes, which can be classified into three categories. The first was related to strengthening the governance of the multi-sectoral system and included: the existence of functional national subcommittees to steer and coordinate the system, the establishment of an inter-sectoral working group to provide scientific and technical support to governance mechanisms, the empowerment of local authorities in the animal surveillance network, the strengthening of coordination between authorities in charge of surveillance in food-producing animals and retail food and the establishment of public-private partnerships for the surveillance of clinical isolates. The second category consisted of strengthening technical and organizational capacities in the different existing surveillance programs. The third category was related to an increased coverage of the national surveillance system, through the implementation of surveillance activities of animal clinical isolates at community level, and the extension of the surveillance in food-producing animals to other commodities and geographical regions (**Figure 7**).

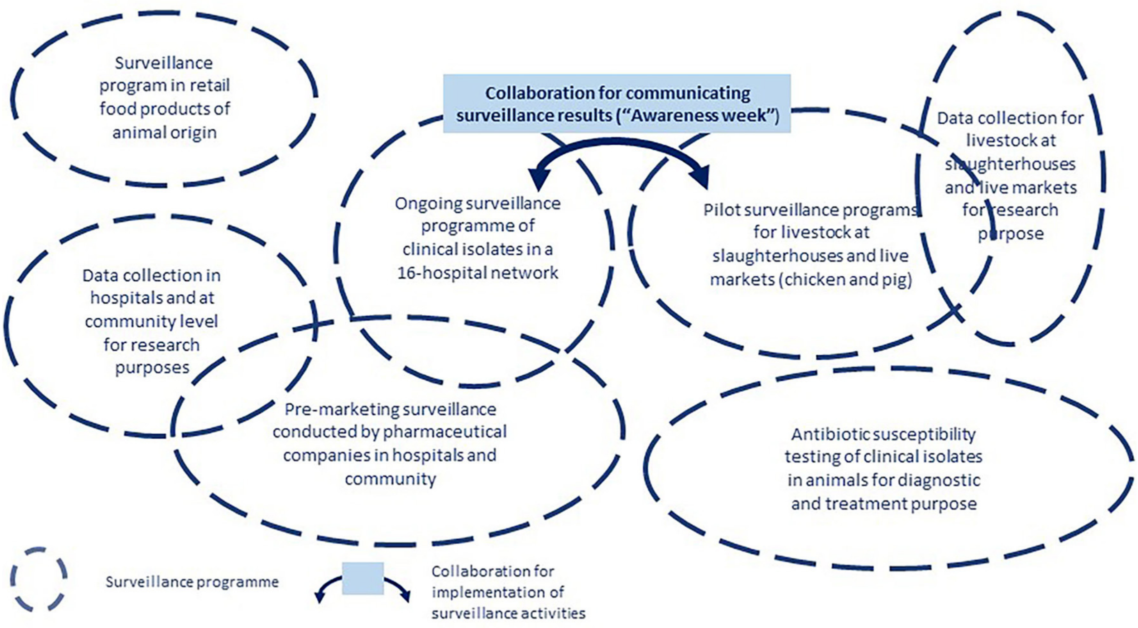


FIGURE 6 | System map of the surveillance of antimicrobial resistance in Vietnam.

The group consisting of animal and food sector professionals worked on identifying actions to improve the capacity of the animal surveillance network, including analytical capabilities, and the inter-sectoral coordination of the national surveillance system. The group constituted of human health professionals worked mainly on defining actions to improve the inter-sectoral mechanisms for the steering, coordination, and scientific and technical support of the national system.

Figure 7 shows the causal links between actions, changes and characteristics of the desired One Health surveillance system to shape the innovation pathway toward the system objective.

In both groups, surveillance of AMR in ecosystems was mentioned and discussed. Both considered it was not a priority, arguing that ecosystems were contaminated by other compartments, either directly through resistant bacteria or indirectly through the release of antibiotic residues, imposing a selection pressure on bacteria present in the environment.

Surveillance of *Salmonella* in France

In France, the participatory process was implemented during three half-day workshops, between April and October 2019. Participants were those present at the meetings of the technical group dedicated to *Salmonella* surveillance but varied over the course of the workshops as shown in **Table 3**. Because of this variation in the audience and of the long period between workshops, the restitution phase of the results previously produced was crucial at the beginning of the second and third workshop. This allowed newcomers to share their knowledge and view so they can be integrated into the co-constructed representations. Other participants used this opportunity to reflect again on the representations in the light of knowledge gained from group work's activities that had taken place between the workshops.

Definition of the Problem

The analysis of participants' expectations regarding their participation in the work group led to the definition of a first concerted objective (**Figure 2**). This was refined during the series of workshops, as the reflection progressed. The final objective was to produce strategic recommendations to improve the collection of data and the circulation of useful information in order to improve the management of the risk related to *Salmonella*. The problem was therefore 2-fold: on the one hand, the improvement of surveillance capacities by strengthening existing surveillance programs or by increasing surveillance coverage, and on the other hand, the improved circulation of information among all the stakeholders involved in *Salmonella* risk management, whether or not they are part of a surveillance program.

Representation of the Current Surveillance System

Stakeholder Diagram and System Map

The revision of the stakeholder diagram proposed by the research team led to the representation of a system that involved 41 different stakeholders operating in 18 surveillance programs (**Figure 8**). These stakeholders belong to the public ($n = 28$) and/or private ($n = 19$) sector, with seven working in both the private and public sectors. They fall into six professional categories: competent authorities ($n = 14$), private operators and professional organizations ($n = 11$), technical or research institutes ($n = 8$), testing laboratories ($n = 7$) or civil society ($n = 1$). They work in the sector of food production ($n = 15$), food safety ($n = 14$), animal health ($n = 12$), human health

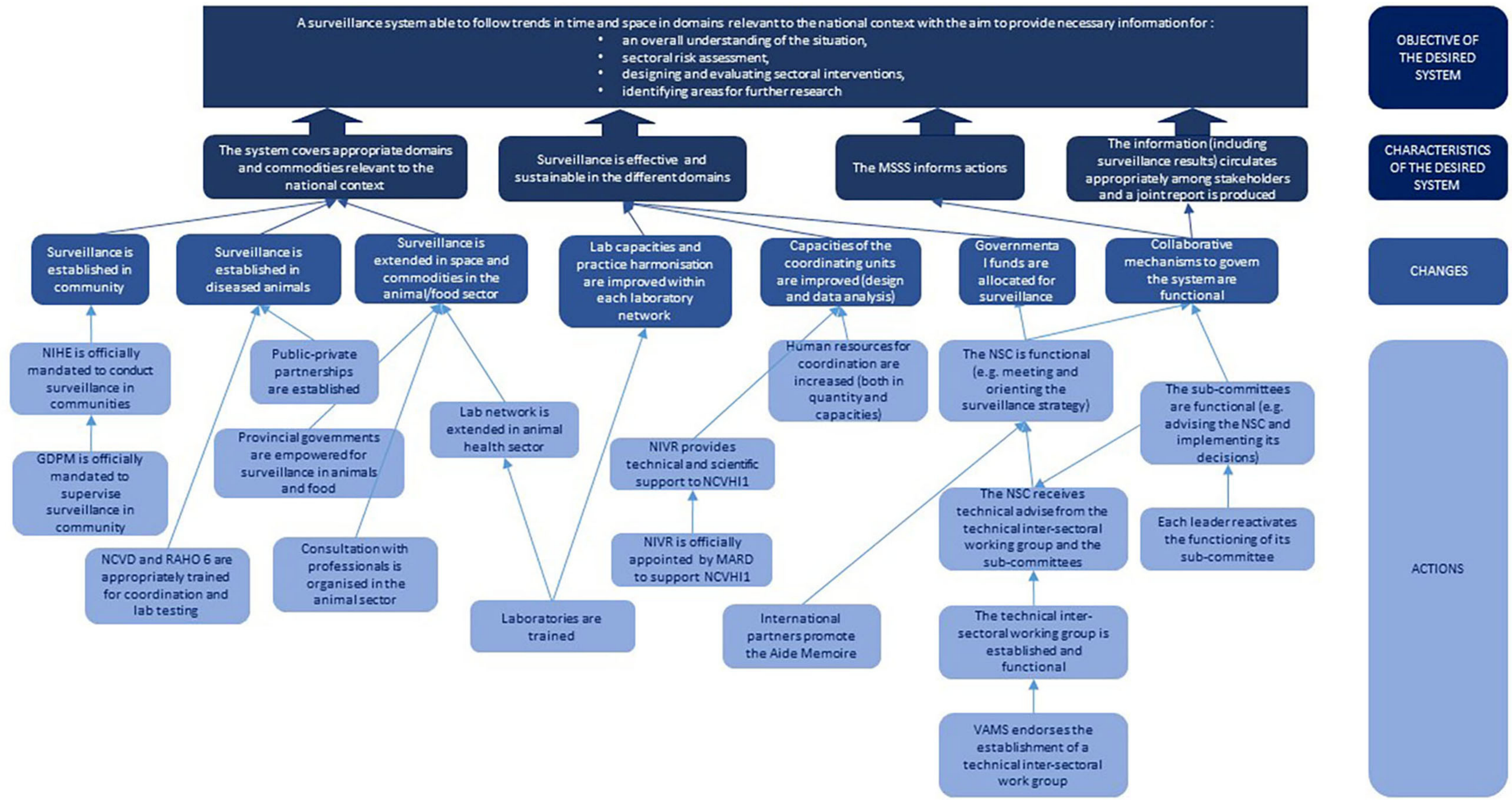


FIGURE 7 | The innovation pathway constructed by participants to the participatory process in Vietnam. GDPM, General department of preventive medicine; MARD Ministry of agriculture and rural development; NCVD, National center for veterinary diagnostic; NCVHI1, National center of veterinary hygiene 1; NIHE, National institute of hygiene and epidemiology; NIVR, National institute of veterinary research; NSC, National steering committee; RAHO 6, Regional animal health office 6; VAMS, Vietnam administration of medical services.

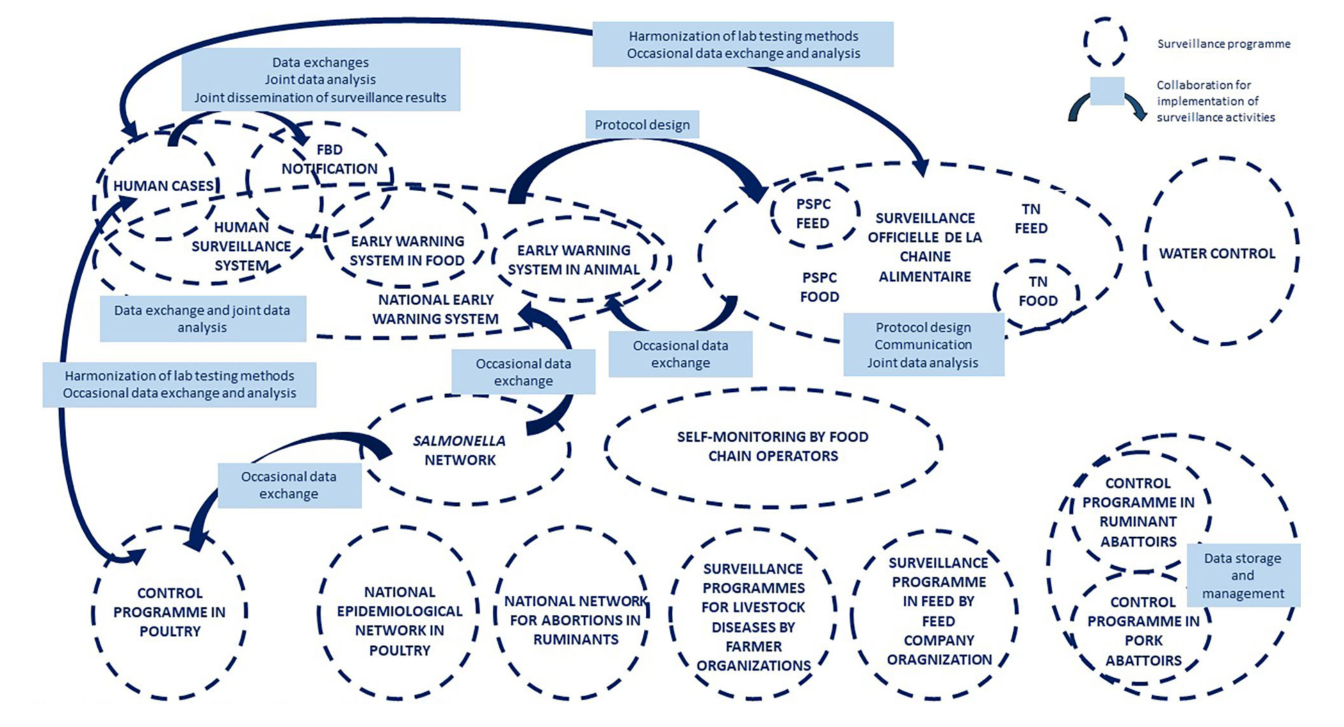


FIGURE 8 | The System map of the surveillance of *Salmonella* in France.

($n = 8$), water production ($n = 1$), or ecosystem health ($n = 1$). The majority of programs (14/18) are sector specific, while others may cover two to four sectors. In total, eight programs cover human food, seven cover animal feed, six cover animal health, two cover human health, and two cover the environment. For the majority of these programs (12/18), coordination is ensured by public authorities. Twelve of them are of a mandatory regulatory nature, while the others rely solely on voluntary action. With the exception of water surveillance and a few isolates from wildlife collected through a laboratory network named "Réseau *Salmonella*," there is very little surveillance activity concerning the natural environment.

The system map highlights the existence of a large number of collaborations for the governance and implementation of surveillance activities (**Figure 8**). However, the connections are not homogeneous within the system. While some programs appear to be isolated, others are highly inter-connected, creating sub-systems within the national system.

Surveillance System SWOT Analysis

According to participants, the major strengths of the current system are the regulatory obligations to report *Salmonella* detections, the strong mobilization of professionals to participate *Salmonella* risk mitigation, the existence of initiatives and mechanisms to allow for data mutualization and exchange, the existence of functional sectoral surveillance programs, and finally the participation in the surveillance effort of all professions and disciplines necessary for the implementation of an integrated approach. However, a poor articulation between existing surveillance programs and an insufficient circulation of information between stakeholders were highlighted. This was ascribed to the absence of collaborative mechanisms for the governance of the national system, which has a negative impact on the quality of the mitigation measures implemented. Surveillance requirements were considered uneven across production sectors (e.g., higher in the poultry sector) and insufficient in the natural environment to gain a good understanding of the transmission of the bacteria. The reconciliation of data from different sources is hindered by technical issues, such as disparity in format, the absence of a centralized system, and the non-systematic characterization of detected isolates. Participants identified a number of opportunities to be seized, such as the existence of functional surveillance programs in certain production sectors (e.g., poultry) that could serve as a model for other sectors, or the current national dynamics around the development of multi-stakeholder surveillance platforms (in animal health and food safety). In addition, it was stressed that substantial human, animal, and food strain characterization data were already available and could be easily compared and, in the future, the comparison between data should be facilitated by the development of new techniques such as high throughput sequencing. On the other hand, a certain number of challenges must be met to achieve the desired surveillance system: lack of resources, inappropriate communication in the event of a *Salmonella*-related health crisis, data ownership, mistrust, and fear of economic or administrative sanctions, which can represent a major obstacle to stakeholder involvement in

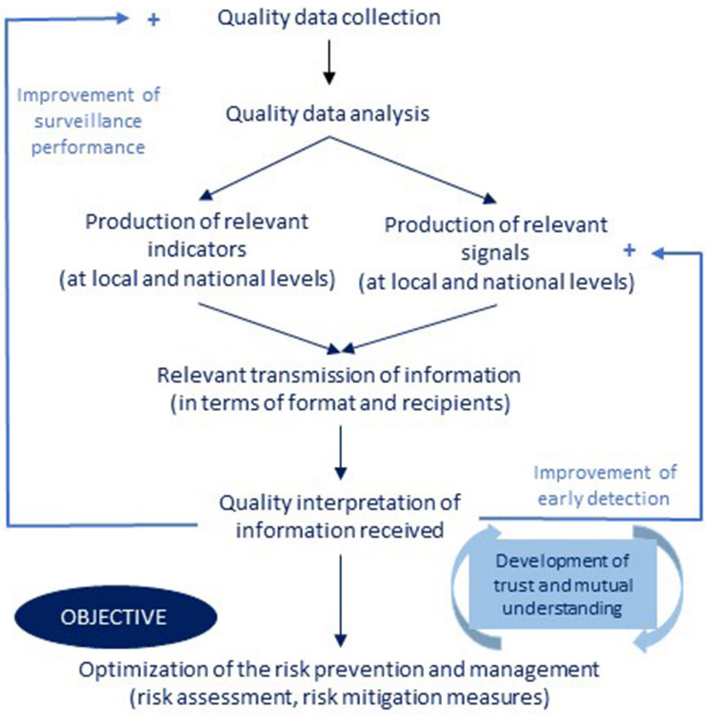


FIGURE 9 | The representation of the desired surveillance system for *Salmonella* in France.

information sharing and the need to change the attitude toward *Salmonella* risk (zero risk is not technically and economically sustainable for the sectors).

Desired Multi-Sectoral Surveillance System

For workshop participants, the desired surveillance system (**Figure 9**) should be able to produce quality information, communicated to the right people in a timely manner, to achieve appropriate management and prevention measures. This involves the collection and analysis of high-quality data to produce indicators and signals that can be shared with risk assessors and managers (operators, authority, risk assessment agency). The implementation of appropriate measures to manage and prevent risk depends on the ability of information users to correctly interpret these indicators and signals. Sharing information between stakeholders should strengthen mutual trust between them, which, through positive feedback, should contribute to improving the flow of information.

Changes Required to Achieve the Desired Surveillance System

Participants identified major changes in the different pre-defined categories (**Figure 10**). In terms of practice, they identified the need to improve the modalities and coverage of passive surveillance, to increase the number of tests done by the food chain operators, and to set up an event-based monitoring system. Concerning knowledge, it appeared necessary to better understand the sources of contamination and the role of the discharge of farm effluents in the transmission of the bacteria. With regard to interactions, the results of official tests (positive and negative) should be transmitted to operators. In the same way, operators should share their results with operators working at the same stage of the food chain but also in other food-chain stages (e.g., between suppliers and clients). Finally, in terms of posture, operators should be better supported by the authorities. The adoption of a notion of measured and shared risk should replace the notion of zero risk.

The changes and the actions identified for their operationalization were combined with the representation of the desired surveillance system to draw the innovation pathway reflecting participant views (**Figure 10**).

DISCUSSION

Participatory Process: Benefits, Caveats, and Facilitation

The participatory process developed and applied to the two case studies demonstrated its ability to engage multiple stakeholders with very different expectations and contrasting technical and social resources. This engagement allowed them to define a shared vision of the desired system and to negotiate the construction of an associated innovation pathway in which each of them could reasonably take part. Although the framework is developed here for the purpose of One Health surveillance, it may be efficiently adapted to other complex systems that require consultation between actors in a context of high uncertainty. Actually, the tools and methods mobilized here have been first

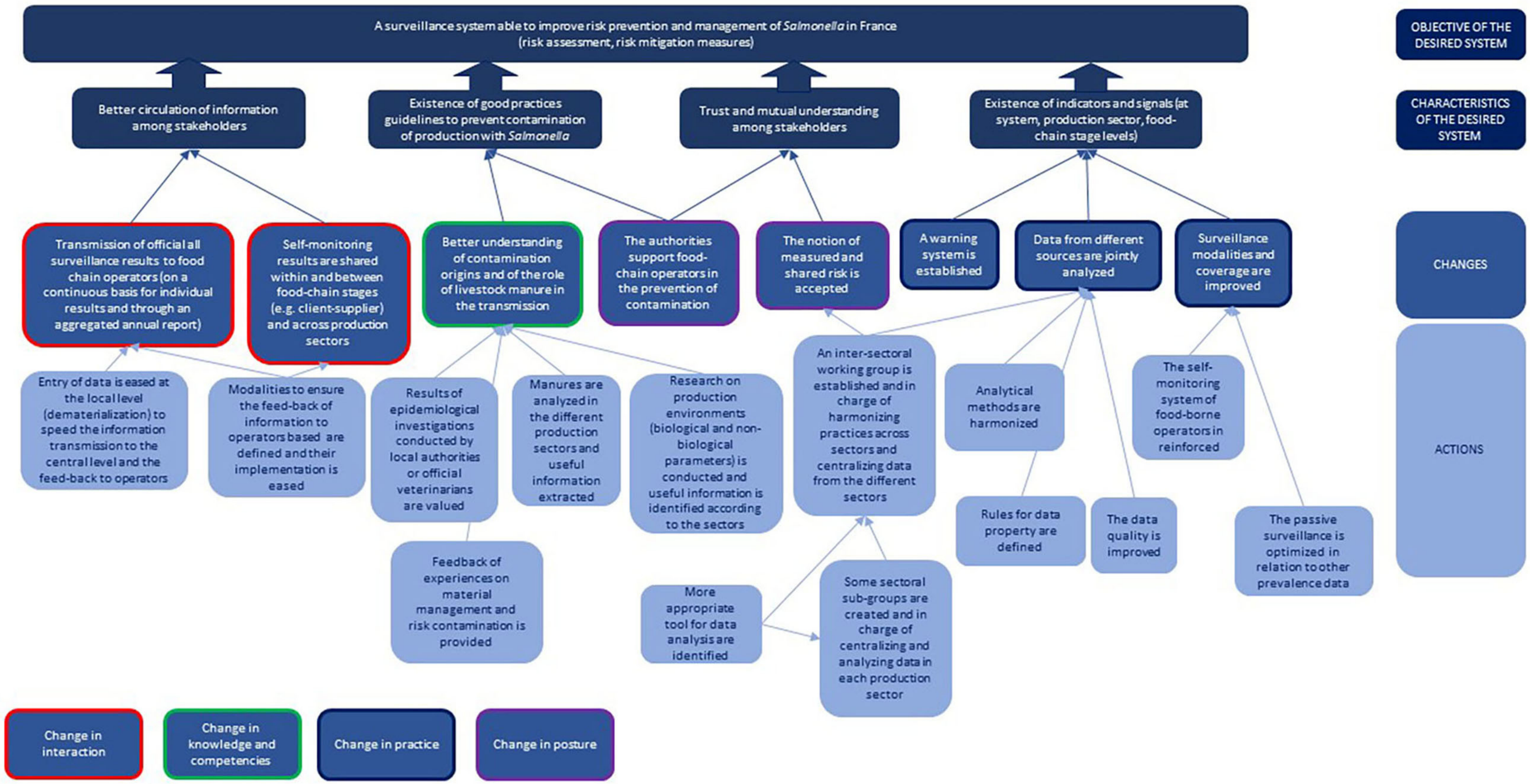


FIGURE 10 | The innovation pathway constructed by the participants to the participatory process in France.

developed to support collective decision-making in situations of conflict over resources (18, 21, 25).

The case studies highlight the applicability of the approach at two distinct levels of participation. Indeed, in the case of Vietnam, the problem was defined by the research team and the participants were invited by the latter to address it. In the case of France, the process was implemented at the request of the work group, which had identified the need to benefit from external support to better define and address the issue. Hence, referring to Pretty's ladder of participation as reviewed by Cornwall (28), the Vietnamese case started as a functional participation and evolved toward an interactive level by leading actors to take a part in own goals definition. In France, the process was triggered by the actors themselves, hence corresponding to self-mobilization. This different level translated into the process could be expressed as a "gradual empowerment" in Vietnam and as an "external coaching" in France.

While the framework is a well-defined structure in four main steps (**Figure 1**), the way they are approached, articulated and facilitated may differ, depending on the context and the information gathered during the process (**Table 1**). As with any participatory approach, the framework is flexible and iterative to adapt to the context of implementation and to accommodate the knowledge shared by the participants, as well as their position and reaction to the process (29, 30). In doing so, the change process toward One Health surveillance is adapted to the system's degree of maturity, in terms of method, goals, and actions. Through its inductive approach, starting by the consolidation of knowledge on the current system, the proposed method automatically adapts to the systems' maturity, strengths, peculiarities, and needs.

The success of such a process depends on the participants involved and the facilitation quality. As in any participatory approach, the representativeness and legitimacy of participants and their adherence to the process remain important issues, as these will impact the quality and relevance of the results (31). Special attention must therefore be paid to the selection of participants and to all the factors that can influence their commitment to the process (time and place of workshops, legitimacy of the organizing institution to initiate such an approach, etc.). In our two case studies, not all categories of stakeholders were represented throughout the process and this must be considered when referring to the workshop outputs for further activities (see section Role of the Process in Enabling Changes Toward One Health Surveillance). In order to overcome this issue, alternative solutions could have been implemented, such as individual consultation of the missing persons and *a posteriori* integration of their knowledge and point of view during the next workshop, after validation by all participants. Then, facilitation quality lies in its ability to accompany the production of knowledge and collective solutions (23). As experienced through the two case studies, the facilitation team may gain from involving three individuals with different postures: a "champion" who is recognized by the participants as legitimate to lead the process (working group coordinator, recognized teacher-researcher), a "naïve" individual who is in a comfortable position to invite participants to clarify and explain their discourse, and an "expert" who formulates relevant probing and follow-up questions. The role of the facilitator is also crucial in ensuring that each participant has a voice in the process. He/she must be able to manage conflicts and power games that may exist between participants, as well as the diversity of temperaments that may co-exist and be an obstacle to the collective process (32). As the proposed approach is adaptive and iterative, facilitators must be flexible in their methodology and be able to readjust their position and the way they carry out the different steps of the process as it unfolds.

Role of the Process in Decreasing Uncertainty Related to One Health Surveillance

The two case studies highlighted the complexity for participants to envision their expectations regarding stronger collaboration and to define required changes for this collaboration to happen. The complexity, as a system characteristic, arises from two main features of the situation: the diversity and number of stakeholders and of their interactions, and the overall uncertainty around the objects under scrutiny. A major uncertainty does indeed prevail around stakeholders' expectations regarding the integration of knowledge and information in a One Health approach. Moreover, it proves difficult for them to anticipate the costs and benefits associated with their involvement in such an evolution of the system. One role of the process is to enable a joint and gradual mastering of the complexity of interactions through shared representations and mutual understanding, and to reduce uncertainty around the desired evolution of the system, by building a group definition of the required integration and relevant operationalization of One Health principles.

The framework is a process of translation and explanation in which participants are encouraged to accurately describe their knowledge of the different elements of the system and to mutually share this information. They have to explain who, in their opinion, are the key stakeholders, their role in the system, the interactions between them, the resources they exchange, the workflow and information flow, the power games at play, the institutional and operational issues and the problems they face. This leads to the formalization of a common language, then mobilized to produce a new shared representation of the whole system. During this process of deconstruction/reconstruction, participants systematically bring knowledge that will decrease the level of uncertainty regarding the expected outputs of the new system, the role of each stakeholder in it, etc.

The process also reveals challenges that stakeholders will face if they engage in the One Health surveillance system, so they can be discussed and anticipated. Meanwhile, the resources to be allocated to overcome these problems can be identified. Elements that would make the One Health system an attractive improvement are highlighted, leading to an understanding of the benefits and costs linked to the changes in practice (15). Finally, discussions make it possible to assess whether integration is feasible, while respecting or maintaining the diversity of co-existing purposes (33).

Influence of the Surveillance System's Maturity on the Process Outputs

These two case studies tackle surveillance systems with contrasting degrees of maturity, as they are under development in Vietnam and already well-established in France.

Despite the differing maturities of their systems, participants in both cases emphasized that the performance of a One Health surveillance system depends essentially on the quality of each of the sectoral programs that are to integrate. Hence, in Vietnam, despite the pressing plea of international organizations in favor of a fully integrated AMR surveillance (3), the participatory process allowed participants to affirm their own positioning centered on more basic needs within each of the One Health components. Thus, they considered the strengthening of surveillance capacities in existing programs as a priority in the mid-term, before considering any data integration. In France, the quality of the data produced by the 18 existing programs was also identified as an essential prerequisite to achieve the objective of the desired One Health surveillance system. Interestingly, integration itself was then considered under the lens of an increase of information utility.

The question of information utility was tackled in the French case study from its user's standpoint, an aspect that was absent from workshops in Vietnam. This sharp contrast was directly linked to the system's maturity. The French system's greater stabilization, in terms of information production, allowed stakeholders to better focus on its use and impact. This user-based vision of health surveillance value and required improvement appears to be a quite recent concern, with methodologies that remain to be elaborated (13). Hence, participants proved able to develop original insights on the operationalization of the One Health concept in surveillance. Beyond collaboration between surveillance programs, the participatory process re-asserts the surveillance system's societal mission, acknowledging the diversity of stakeholders involved in risk prevention and management.

Role of the Process in Enabling Changes Toward One Health Surveillance

The proposed method is an inductive and socio-constructivist action-research tool. Its objective is to capture the diversity of participants' knowledge about the system, stakeholders' practices, posture and capacities, and the interactions between them. On this basis, new knowledge emerges by combining and aggregating these sources of information, leading to the construction of shared visual representations (stakeholder diagram, system map, innovation pathway, etc.). These representations constitute together a conceptual framework to which participants can reasonably adhere. It is therefore not so much the conceptual framework in itself as its collective development that is expected to enable change (23). Indeed, during this development, participants are engaged in a social learning process that leads to a shared understanding of the situation and of the desired future (34–36). They have to listen to each other, make the effort to translate their ideas so that they are intelligible to others, and change their understanding and view of the current and desired system in order to integrate the information expressed by the others. This social learning process leading to the co-constructed and negotiated conceptual framework is expected to be conducive to the emergence of the collective action toward a One Health surveillance system (37).

As for other processes relying on knowledge co-production, the proposed framework has envisioned impacts in terms of collective actions. However, it does not have the capacity to measure them (33, 38). Indeed, it does not ensure that the innovation pathway constructed is the most appropriate one, that the actions identified are the most relevant or that the changes will actually take place. It represents a basis for later steps, which will ascertain or correct the intended plan, also through the inclusion of additional stakeholders who did not take part to the co-construction of the innovation pathway (e.g., local authorities). After revision, consolidation and prioritization of identified actions, the innovation pathway can be used as a working basis to develop operational recommendations and an action plan for the implementation of the desired surveillance system (21). Simulation exercises in the form of role-plays or board games can also be organized to test the proposed modalities, identify gaps and redefine them if necessary (36). Subsequently, an evaluation of the collaboration should also be envisaged, to check for the validity of identified pathways, their degree of realization and their re-orientation where needed. Obviously, these later activities would all gain from adopting the same participatory approach and could be included in the current framework, creating an additional step for the monitoring and evaluation of the system's development.

In Vietnam, no concrete action was taken following these collective workshops, even though the participants recognized that they had gained knowledge and mutual understanding and forged strong interpersonal relationships that would be beneficial for future collaboration. In France, following this work, a new workshop was organized to propose concrete and operational actions based on the outputs of the participatory process. A permanent work group dedicated to *Salmonella* surveillance was then established with the mission of coordinating the operationalization of these actions. This work group is transversal to the French epidemiological surveillance platforms for animal diseases and for the food chain, which includes representatives of the human health sector. This difference in impact between the two case studies is likely to be related to the degree of maturity of the system.

CONCLUSION

The participatory process described here produces a conceptual framework that can be mobilized to generate collective action. As in transdisciplinary processes, the outcomes of the framework are not predetermined (33). This makes necessary to adapt the means of its implementation to the context and to remain flexible throughout the whole course of the process. Its objective is not to go as far as developing a detailed action plan for change implementation, but to create an environment conducive to discussion and to generate technical elements that stakeholders can then use to plan their future actions. The consultation and negotiation process initiated through the participatory workshops lays the foundation for a new partnership working toward a more integrated approach to surveillance, in which road maps can be produced and collaborative actions planned. A major challenge of this type of approach is to identify the exact nature of their impacts in terms of collective actions, leadership and decision-making, and to develop robust methods to measure them.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because data cannot be shared before previous authorization from participants to the collective workshops. Requests to access the datasets should be directed to marion.bordier@cirad.fr.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethical Review Board for Biomedical Research of the Hanoi University of Public Health in Vietnam and the Ethical Committee for research of Paris-Saclay University in France. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MB and AB designed and coordinated the study, analyzed the results, and drafted the manuscript. FG initiated the study, participated in its design, contributed to the analysis, interpretation of results, and to the finalization of the manuscript. PP-D and RL participated to the implementation of the study, the analysis of the results, and in finalizing the manuscript. NA-M participated in the discussion of the results and in finalizing the manuscript. All authors read and approved the final manuscript.

FUNDING

This work was funded in part by the French Ministry of Agriculture, the GREASE platform in partnership (https://www.grease-network.org/), and the French Embassy in Vietnam. Participants attended the workshops on their own funds.

ACKNOWLEDGMENTS

We would like to warmly thank the participants in the series of workshops held in France and Vietnam, as well as the National Institute of Veterinary Research and the French Agency for Food, Environmental and Occupational Health and Safety for hosting these workshops in conditions conducive to discussion and innovation. We would also like to thank Panomsak Promburom, Emeline Hassenforder, and Nicolas Salliou for their contribution to the development of the socio-technical framework.

REFERENCES

1. Rüegg SR, Buttigieg SC, Goutard FL, Binot A, Morand S, Thys S, et al. Editorial: concepts and experiences in framing, integration and evaluation of One Health and ecohealth. *Front Vet Sci*. (2019) 6:155. doi: 10.3389/fvets.2019.00155
2. Food Agriculture Organization. *The FAO-OIE-WHO Collaboration. Sharing Responsibilities and Coordinating Global Activities to Address Health Risks at the Animal-Human-Ecosystems Interfaces.* (2011). Available online at: https://www.who.int/influenza/resources/documents/tripartite_concept_note_hanoi/en/ (accessed November 20, 2020).
3. World Health Organization. *Integrated Surveillance of Antimicrobial Resistance in Foodborne Bacteria.* (2017). Available online at: http://www.who.int/foodsafety/publications/agisar_guidance2017/en/ (accessed November 20, 2020).
4. Babo Martins S, Rushton J, Stärk KDC. Economic assessment of zoonoses surveillance in a 'One Health' context: a conceptual framework. *Zoonoses Public Health*. (2016) 63:386–95. doi: 10.1111/zph.12239
5. Stärk KDC, Arroyo Kuribreña M, Dauphin G, Vokaty S, Ward MP, Wieland B, et al. One health surveillance – more than a buzz word? *Prev Vet Med*. (2015) 120:124–30. doi: 10.1016/j.prevetmed.2015.01.019
6. Aenishaenslin C, Häsler B, Ravel A, Parmley J, Stärk K, Buckeridge D. Evidence needed for antimicrobial resistance surveillance systems. *Bull World Health*. (2019) 97:283–9. doi: 10.2471/BLT.18.218917
7. Bordier M, Binot A, Pauchard Q, Nguyen DT, Trung TN, Fortané N, et al. Antibiotic resistance in Vietnam: moving towards a One Health surveillance system. *BMC Public Health*. (2018) 18:1136. doi: 10.1186/s12889-018-6022-4
8. Bordier M, Uea-Anuwong T, Binot A, Hendrikx P, Goutard FL. Characteristics of One Health surveillance systems: a systematic literature review. *Prev Vet Med*. (2018) 181:104560. doi: 10.1016/j.prevetmed.2018.10.005
9. Johnson I, Hansen A, Bi P. The challenges of implementing an integrated One Health surveillance system in Australia. *Zoonoses Public Health*. (2018) 65:e229–36. doi: 10.1111/zph.12433
10. Kayunze KA, Kiwara A, Lyamuya E, Kambarage DM, Rushton J, Coker R. Practice of One Health approaches: bridges and barriers in Tanzania. *Onderstepoort J Vet Res*. (2014) 81:8. doi: 10.4102/ojvr.v81i2.733
11. Mitchell ME, Alders R, Unger F, Nguyen-Viet H, Le TTH, Toribio JA. The challenges of investigating antimicrobial resistance in Vietnam-what benefits does a One Health approach offer the animal and human health sectors? *BMC Public Health*. (2020) 20:1–12. doi: 10.1186/s12889-020-8319-3
12. Uchtmann N, Herrmann JA, Hahn EC, Beasley VR. Barriers to, efforts in, and optimization of integrated One Health surveillance: a review and synthesis. *EcoHealth*. (2015) 12:368–84. doi: 10.1007/s10393-015-1022-7
13. Antoine-Moussiaux N, Vandenberg O, Kozlakidis Z, Aenishaenslin C, Peyre M, Roche M, et al. Valuing health surveillance as an information system: interdisciplinary insights. *Front Public Health*. (2019) 7:138. doi: 10.3389/fpubh.2019.00138
14. Barnett T, Pfeiffer DU, Hoque MdA, Giasuddi M, Flora MS, Biswas PK, Debnath N, et al. Practising co-production and interdisciplinarity: challenges and implications for One Health research. *Prev Vet Med*. (2020) 177:104949. doi: 10.1016/j.prevetmed.2020.104949
15. Figuié M. L'action collective face au défi des zoonoses émergentes. In: Morand S, Figuié M, editors. *Emergence de Maladies Infectieuses: Risques et Enjeux de Société*. Versailles: Quae (2016) 79–104.

16. Fortané N. La surveillance comme dispositif-frontière: la triple ontologie des bactéries résistantes d'origine animale. *Revue D'anthropologie Connaissances.* (2015) 9:265. doi: 10.3917/rac.027.0265
17. Daré WA, Van Paassen R, Ducrot R, Mathevet J, Queste G, Trébuil C, et al. Apprentissage des interdépendances et des dynamiques. In: Etienne M, editor. *La Modélisation D'accompagnement: Une Démarche Participative en Appui au Développement Durable*. Versailles: Quae éditions (2010). p. 223–50.
18. Binot A, Duboz R, Promburom P, Phimpraphai W, Cappelle J, Lajaunie C, et al. A framework to promote collective action within the One *Health* community of practice: using participatory modelling to enable interdisciplinary, cross-sectoral and multi-level integration. *One Health.* (2015) 1:44–8. doi: 10.1016/j.onehlt.2015.09.001
19. Reed MS. Stakeholder participation for environmental management: a literature review. *Bio Conserv*. (2008) 141:2417–31. doi: 10.1016/j.biocon.2008.07.014
20. Bordier M, Delavenne C, Nguyen DTT, Goutard FL, Hendrikx P. One Health surveillance: a matrix to evaluate multisectoral collaboration. *Front Vet Sci*. (2019) 6:109. doi: 10.3389/fvets.2019.00109
21. Etienne M, Du Toit DR, Pollard S. ARDI: a co-construction method for participatory modeling in natural resources management. *Econ Sociol.* (2011) 16:44. doi: 10.5751/ES-03748-160144
22. Etienne M. Companion modelling: a tool for dialogue and concertation in BIOSPHERE RESERVES. *UNESCO-MAB Technical Notes.* (2006) 1:44–52.
23. Duboz R, Echaubard P, Promburom P, Kilvington M, Ross H, Allen W, et al. Systems thinking in practice: participatory modeling as a foundation for integrated approaches to health. *Front Vet Sci.* (2018) 5:303. doi: 10.3389/fvets.2018.00303
24. Helms MM, Nixon J. Exploring SWOT analysis – where are we now? A review of academic research from the last decade. *J Strategy Manag*. (2010) 3:215–51. doi: 10.1108/17554251011064837
25. Blundo-Canto G, Triomphe B, Faure G, Barret D, de Romemont A, Hainzelin E. Building a culture of impact in an international agricultural research organization: process and reflective learning. *Res Eval.* (2019) 28:136–44. doi: 10.1093/reseval/rvy033
26. Faure G, Blundo-Canto G, Devaux-Spartarakis A, Le Guerroué JL, Mathé S, Temple L, et al. A participatory method to assess the contribution of agricultural research to societal changes in developing countries. *Res Eval.* (2020) 29:1–13. doi: 10.1093/reseval/rvz036
27. Douthwaite B, Kuby T, van de Fliert E, Schulz S. Impact pathway evaluation: an approach for achieving and attributing impact in complex systems. *Agric Syst*. (2003) 78:43–265. doi: 10.1016/S0308-521X(03)00128-8
28. Cornwall A. Unpacking 'participation': models, meanings practices. *Commun Dev J*. (2008) 43:269–83. doi: 10.1093/cdj/bsn010
29. Mariner JC, Paskin R. *Manual on Participatory Epidemiology: Methods for the Collection of Action-Oriented Epidemiological Intelligence.* Rome: Food and Agriculture Organization of the United Nations (2000). p. 81. http://www.fao.org/docrep/003/x8833e/x8833e00.htm (accessed January 2021).
30. Pretty JN. Participatory learning for sustainable agriculture. *World Dev.* (1995) 23:1247–63. doi: 10.1016/0305-750X(95)00046-F
31. Glicken J. Getting stakeholder participation 'right': a discussion of participatory processes and possible pitfalls. *Environ Sci Policy.* (2000) 3:305–10. doi: 10.1016/S1462-9011(00)00105-2
32. Pretty JN, Guijt I, Thompson J, Scoones I. *Participatory Learning and Action: A Trainer's Guide*. London: The International Institute for Environmental and Development (1995).
33. Pohl C, Thompson Klein J, Hoffmann S, Mitchell C, Fam D. Conceptualising transdisciplinary integration as a multidimensional interactive process. *Environ Sci Policy.* (2021) 118:18-26. doi: 10.1016/j.envsci.2020.12.005
34. Von Schönfeld, KC, Tan W, Wiekens C, Janssen-Janse L. *Unpacking social learning in* planning: who learns what from whom? *Urban Res Prac.* (2019) 13:411–33. doi: 10.1080/17535069.2019.1576216
35. Trebuil G, Ruault C, Soulard C, Bousquet F. Les démarches ComMod et Gerdal d'accompagnement de collectifs multi-acteurs pour faciliter l'innovation dans les agroécosystèmes. In: Guy F, Yuna C, Frédéric G, Ludovic T, Jean-Marc T, editors. *Innovation et Développement Dans les Systèmes Agricoles et Alimentaires*. Versailles: Ed. Quae (2018). p. 179–93.
36. Andreotti F, Speelman EN, Van den Meersche K, Allinne C. Combining participatory games and backcasting to support collective scenario evaluation: an action research approach for sustainable agroforestry landscape management. *Sustain Sci.* (2020) 15:1383–99. doi: 10.1007/s11625-020-00829-3
37. Pohl C, Hirsch Hadorn G. Methodological challenges of transdisciplinary research. *Nat Sci Soc*. (2008) 16:111–21. doi: 10.1051/nss:2008035
38. Schneider F, Giger M, Harari N, Moser S, Oberlack C, Providoli I, et al. Transdisciplinary co-production of knowledge and sustainability transformations: three generic mechanisms of impact generation. *Environ Sci Policy*. (2019) 102:26–35. doi: 10.1016/j.envsci.2019.08.017

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.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 04 June 2021
doi: 10.3389/fvets.2021.641448

Check for updates

Potential and Challenges of Community-Based Surveillance in Animal Health: A Pilot Study Among Equine Owners in Switzerland

Ranya Özçelik[1], Franziska Remy-Wohlfender[2], Susanne Küker[1], Vivianne Visschers[3], Daniela Hadorn[4] and Salome Dürr[1]*

[1] Veterinary Public Health Institute, Vetsuisse Faculty, University of Bern, Bern, Switzerland, [2] ISME Equine Clinic Bern, Vetsuisse Faculty, University of Bern, Bern, Switzerland, [3] School of Applied Psychology, University of Applied Sciences and Arts Northwestern Switzerland, Olten, Switzerland, [4] Federal Food Safety and Veterinary Office, Bern, Switzerland

OPEN ACCESS

Edited by:
Roswitha Merle,
Freie Universität Berlin, Germany

Reviewed by:
Nicolai G. W. Denzin,
Friedrich Loeffler Institute, Germany
Cécile Aenishaenslin,
Université de Montréal, Canada

***Correspondence:**
Ranya Özçelik
ranya.oezcelik@vetsuisse.unibe.ch

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: 14 December 2020
Accepted: 28 February 2021
Published: 04 June 2021

Citation:
Özçelik R, Remy-Wohlfender F, Küker S, Visschers V, Hadorn D and Dürr S (2021) Potential and Challenges of Community-Based Surveillance in Animal Health: A Pilot Study Among Equine Owners in Switzerland. Front. Vet. Sci. 8:641448. doi: 10.3389/fvets.2021.641448

Animal owners' potential to observe and report clinical signs, as the persons with the closest contact to their animals, is an often neglected source of information in surveillance. Allowing community members other than health care professionals, such as animal owners, to report health events can contribute to close current surveillance gaps and enhance early detection. In the present study, we tested a community-based surveillance (CBS) approach in the equine community in Switzerland. We aimed at revealing the attitudes and intentions of equine owners toward reporting clinical signs by making use of an online questionnaire. We further set up and operated an online CBS tool, named Equi-Commun. Finally, we investigated potential reasons for the lack of its use by applying qualitative telephone interviews. The majority of the respondents of the online questionnaire (65.5%, 707/1,078) answered that they could see themselves reporting clinical observations of their equine. The multivariate logistic regression analysis indicated that French-speaking equine owners and those belonging to the positive attitude cluster are more likely to report to a CBS tool. Equi-Commun operated between October 2018 and December 2019 yet received only four reports. With the addition of qualitative interviews, we identified three critical, interlinked issues that may have led to the non-use of Equi-Commun within the Swiss equine community: (1) for successfully implementing CBS, the need for surveillance within the community of interest must be given; (2) the respective population under surveillance, here the equine, needs to show enough clinical cases for owners to be able to maintain the memory of an existing tool and its possible use; and (3) targeted and high effort communication of the system is key for its success. While CBS relying only on lay animal owners, complementary to existing surveillance systems, could potentially provide a good proxy of timely surveillance data, it is questionable whether the added value of generated surveillance knowledge is in balance with efforts necessary to implement a successful system. With this study, we showcased both the potential and challenges of CBS in animal health, as this may be of relevance and guidance for future initiatives.

Keywords: equine, animal health surveillance, equine owner, transdisciplinary, surveillance, community, surveillance system, community-based surveillance

INTRODUCTION

Animal health surveillance has been developing continuously over the past decades, providing new concepts, approaches, and methods for improvement and refinement of animal health (1–3). Health professionals, such as veterinarians, play a crucial role in surveillance. They are involved in routinely collecting animal health and production data, such as for syndromic surveillance and active surveillance programs, as well as in providing necropsy reports and diagnostic laboratory data (3–8). Surveillance data, except for syndromic surveillance, predominantly depend on clinical cases being presented to health professionals (9). Yet not all diseased humans or animals seek–or are brought to receive–medical care, for reasons such as concern about health care costs and the individual person's perception of a certain clinical case being severe enough to be presented to a health care professional (10–13). Meanwhile, animal owners' potential to observe clinical signs, as the persons with the closest contact to their animals, is often neglected. Inclusion of animal owners in animal health surveillance, in the frame of community-based surveillance (CBS), could complement and strengthen existing surveillance efforts.

Up to date, the term CBS has mainly been used in the context of public health and One Health surveillance, while predominantly implemented in low- and lower-income countries (14). The World Health Organization (WHO) defined the term CBS in the context of public health as follows: "CBS is the systematic detection and reporting of events of public health significance within a community by community members." (15). CBS has been shown to have the potential to close surveillance gaps by complementing existing surveillance systems, especially in settings where logistic or socio-cultural factors for accessing certain populations and generating data are limited or personnel and financial resources are tight (14, 16, 17). As a recent example, a CBS tool provided by the International Red Cross and Norwegian Red Cross (https://www.cbsrc.org/) organizations allowed the detection of the first coronavirus disease 2019 (COVID-19) case in Somaliland (18).

While an official definition and uniform use for the term CBS in animal health is lacking, there are various approaches and initiatives making use of community members' involvement and engagement in animal health surveillance. Such approaches are embedded in participatory surveillance, participatory epidemiology, citizen science, and owner-based reporting of health-related data (19–22). As an example, a CBS system established up-on community animal health workers in Tanzania has previously shown to enhance surveillance capacity by increasing spatial coverage of surveillance systems and deliver timely data on community-based disease observations in livestock (23). Whether it is by deploying trained staff or by lay people, CBS can contribute to close current surveillance gaps and enhance early detection by allowing community members other than designated health care professionals to report and alert for health events (24). Although CBS systems in animal health are predominantly described from low- and middle-income countries, examples of systems collecting animal health data by owners also exist in developed countries. In many European countries, farmers are obliged to systematically record diverse health data of their livestock, such as antimicrobial use, abortions, and deaths (25–27). However, many such systems are only in place because of binding regulations and laws, therefore are not based on voluntary compliance of animal owners.

Within the field of equine health, multiple studies have described the use of owner-based reports to limit knowledge gaps of certain health disorders. In a cross-sectional survey in Australia, equine owners' capacity to observe the health of their own equine was used to determine the prevalence of a wide range of health disorders (28). Likewise, in Great Britain a survey was performed among equine owners over a 2-year period on preventive health care measures and certain disease prevalence of their equine (29). In another study from Great Britain, equine owners were asked to report laminitis episodes through a web-based form for an overall study period of 2 years to overcome the suspected underestimation of veterinary-diagnosed equine laminitis incidences (21). While each of these studies made use of equine owners' capability to observe and report clinical signs, they have in common that reporting was temporally limited. They thus only allowed a cross-sectional insight to current disease events based on the knowledge and observations of equine owners, however did not provide continuous surveillance. The French epidemiological network for equine diseases (Réseau d'Epidémio-Surveillance en Pathologie Equine, "RESPE") announced the implementation of the project VigiRespe, which was created to complement existing veterinary surveillance data and increase sensitivity with the help of observations by equine owners (30–32). Yet peer-reviewed publications regarding their experiences on the system are lacking up to date. Thus, to the best of our knowledge, attempts to include non-sentinel and voluntary equine owners for continuous disease surveillance have not been investigated yet.

The surveillance of equine health in Switzerland currently includes the mandatory reporting of 17 notifiable diseases according to the Swiss animal health law (Federal Council of Switzerland, 1995). In addition, Equinella (www.equinella.ch), a veterinary-based voluntary surveillance system for clinical signs and equine diseases not notifiable by the Swiss law, is in place (33–35). During a presentation on Equinella at the 2016 Swiss annual scientific conference and network of equine health research, equine practitioners as well as various stakeholders from the Swiss equine industry arouse the question whether equine owners could also contribute to Equinella. This input from the equine community showed the interest to participate in surveillance systems and was one of the drivers of the here presented CBS approach.

In the present study, we aimed to reveal the perception, attitude, and intention of Swiss equine owners toward CBS and report clinical signs of their equine. First, a cross-sectional online questionnaire was sent to Swiss equine owners. Second, we set up and operated an online CBS tool, named Equi-Commun. The aim of Equi-Commun was to assess the benefits of surveillance data derived from equine owners compared with already existing surveillance data from Equinella in terms of timeliness of reporting, as well as data quantity and quality. It, however, received only four reports during the 1-year pilot phase and was put to rest due to non-use. We, therefore, finally investigated potential reasons for the lack of its use by applying qualitative telephone interviews among equine owners. In summary, we present and discuss the potential and challenges of CBS as well as possible reasons for the lack of compliance of equine owners to a CBS system, which may be informative for animal health surveillance systems beyond equine health.

MATERIALS AND METHODS

Online Survey

The online survey aimed at revealing the perception, attitudes and intention of equine owners in Switzerland toward CBS and toward reporting clinical signs of their equine, as well as determining factors (positive and negative beliefs and demographic parameters) influencing these attitudes and intentions. In addition, information on clinical signs in equines discovered by their owners during the last 12 months was interrogated to generate a baseline value on cases that may be reported to the CBS system.

Questionnaire Design and Launch, and Data Export

The questionnaire (**Supplementary Material 1**) was developed by a transdisciplinary team of epidemiologists, veterinarians, Veterinary Public Health specialists, and a psychologist. It contained 31 questions, of which 19 were mandatory, including single response, multiple choice, 5- and 6-point Likert scale, and free-text questions, embedded in four main parts; (1) information on equine owned and/or kept on the own premises, (2) clinical signs observed among their equine and/or the equine kept on the own premises within the last year, (3) intention to use and attitude toward a proposed CBS tool and, (4) demographic data of the respondent. To enable participants to reflect on the questions regarding their attitude toward a CBS tool, a description of the not yet launched "Equi-Commun" was provided within the questionnaire (**Supplementary Material 1**, section C, question 16). The questionnaire was designed in German and later translated into French and Italian. Once finalized, the survey was programmed in LimeSurvey (https://www.limesurvey.org/) and pre-tested by 24 equine owners in all three languages and thereafter adapted according to their feedback. Persons registered to the Agate portal (36) (mandatory register for equine owners in Switzerland), owning or accommodating at least one equine (horses, ponies, donkeys, or mules), and having an e-mail address build the sampling frame (∼53,000 equine owners). A sample of 7,500 equine owners was randomly retrieved from the sampling frame. This sample size was calculated using a design prevalence of 50% (to provide the largest samples size), a confidence level of 95%, a precision rate of 5%, and an estimated response rate of 20%. The questionnaire was sent out as a link within an e-mail to all 7,500 recipients on July 11, 2018 by the Food Safety and Veterinary Office (FSVO). Participants were offered to leave their e-mail address at the end of the questionnaire to be informed about future steps regarding the project. A reminder e-mail for the online questionnaire was sent to all recipients after 1 week. The survey was accessible for 2 weeks in total. Data were exported from LimeSurvey in Microsoft Excel for data analysis. According to Swiss legislation, studies that do not collect sensitive human personal data nor human health-related information do not require an ethical approval. This also applies to the telephone interviews (Qualitative Interviews section).

Data Analysis

Only fully completed questionnaires were taken into account for the statistical analysis. The analyses were conducted in R statistical software version 3.6.2 (37). Descriptive statistics on the study population and the intention of equine owners to report to the CBS system was performed.

The attitude toward CBS was assessed using three questions from the survey, two Likert scales and one multiple choice questions (questions 21, 22, and 23 in the questionnaire, **Supplementary Table 1**). Factors captured by these questions covered positive and negative beliefs, such as the perceived value of equine health, incentives for participation in the form of free information or economic benefits, and reasons for not wanting to participate. We conducted a Multiple Component Analysis (MCA) to group respondents according to the answers to these three questions using the R package FactoMineR (38). Results from the MCA were used to classify respondents into hierarchical clusters (further referred to as "attitude cluster") using the Hierarchical Clustering on Principal Components (HCPC) function of the FactoMineR package. The variable *attitude cluster* was used as an explanatory variable in the logistic regression analysis.

One question from the survey was used to evaluate the self-reported intention to contribute to the CBS tool (question 18 in the questionnaire, **Supplementary Material 1**). This question was asking whether respondents could imagine themselves reporting to a CBS tool. The responses to the 5-point Likert scale of this question were transformed into a binary factor by aggregating "certainly yes," "presumably yes," and "maybe" as positive answers (707/1,078 answers) versus "certainly no" and "presumably no" (371/1,078 answers) as negative answers. This binary outcome was used as the outcome variable (*would report*) in a logistic regression analysis investigating factors influencing the intention to contribute to a CBS tool.

First, univariate logistic regression models were built with *age*, *gender*, *type of ownership*, *type of premise*, *sum of clinical signs observed during the past year*, *profession*, *language*, *frequency of visiting the equine*, *transport of equine*, and *attitude cluster* being explanatory variables, whereas *would report* was selected as the outcome variable (**Table 1**). Second, multivariable regression models were built with variables associated with a $p < 0.2$ in the univariate regression models. The final model was identified by stepwise backwards selection of the explanatory variables choosing the model with the lowest Akaike's Information Criteria (AIC) as selection criteria. Variables with coefficient p-values of <0.05 were considered as statistically significant in the final multivariable model.

TABLE 1 | Description of the characteristics of equine owners from fully completed questionnaires, $n = 1,078$.

Variable	Category	Value (n)	Percentage (%)
Age	Average	48.6	–
	Median	50	–
	IQR	39–57	–
Gender	Women	834	77.4
	Men	219	20.3
	Prefer not to say	25	2.3
Language	German	868	80.5
	French	194	18.0
	Italian	16	1.5
Type of ownership	Equine owner	604	56.0
	Equine and premise owner (both)	401	37.2
	Premise owner	73	6.8
Type of premise	Agricultural farm with equine only or equine and other livestock	558	51.7
	Equine on own private ground	295	27.4
	Equine pension premise	196	18.2
	Unknown	23	2.1
	Other (breeding establishment, animal park, training establishment)	6	0.6
Sum of clinical signs observed during	In total by all respondents	17,016	–
the past year	Median per respondent	4	–
	Range per respondent	0–340	–
	IQR	1–11	–
Attitude cluster	Highly positive attitude cluster	446	41.4
	Moderately positive attitude cluster	563	52.2
	Negative attitude cluster	69	6.4
Profession	Working with equine	160	14.8
	Human health care	165	14.5
	Animal health care	40	3.7
	Farmer	154	15.2
	I prefer not to say	138	12.8
	Other	430	39.9
Frequency of visiting the equine	Lives at the same premise	343	31.8
	Once a day at least	498	46.2
	Multiple times per week	197	18.3
	Once a week or more seldom	40	3.7
Transport of equine	Yes	598	55.5
	No	490	44.5

These variables were used in the regression analysis to explore factors influencing the intention toward community-based surveillance (CBS) and the CBS tool Equi-Commun.

CBS Tool Development and Testing

The CBS tool Equi-Commun was conceptually designed following the structure of the veterinary-based voluntary surveillance system Equinella (33–35). Print-screens of the tool user interface are presented in the supplementary materials (**Supplementary Figure 1**). The publicly accessible online tool was technically implemented by a professional IT company (https://www.4eyes.ch/#start) and went live on October 22, 2018. Equi-Commun was addressed to equine owners [further referred to as reporting person(s)] to report observation on clinical signs of their equine as soon as they are observed. Reporting persons were given the option to choose whether or not to register to the system and, thus, create a personal login before reporting their observation. Registration came along with the advantage to access a login secured internal space with a list of previous own reports and automatic completion of information on previously registered equine (name, age, location). For each record, the following data had to be registered on Equi-Commun: name of the affected equine (manual entry), location and postal code of the equine (both manual entries yet interconnected with each other), number of equine on the premise of the reported equine (categorical list of options), observed clinical sign (at least one has to be selected from a predefined list of options), date of onset of the observed sign(s) (date selection from calendar), and duration of the observed sign(s) (categorical list of options). In addition, whether or not a veterinarian was contacted, and in case yes, who this was (manual entry), when the visit took place (date selection from calendar), and the diagnosis made by the veterinarian (manual entry) was requested as optional data. If the reporting person registered to the system for the first time, surname and e-mail address were requested as obligatory, and the primary responsible veterinarian as well as how the person knew about Equi-Commun was requested as optional data. When a record was submitted, an automatic response was generated on the website stating that the report was successfully submitted. Simultaneously, the Equi-Commun team was automatically notified on the submitted report. In general, by accepting the term and conditions stated at the end of each report submission, reporting persons were obliged to agree that the data provided can be used for research purposes in an anonymized version. An ethical approval for collecting CBS data of equines through equine owners was not necessary according to Swiss legislation.

In multiple rounds, the online tool was tested by the authors, the project supporting team of the FSVO, and the equine owners for practicability, logic, user-friendliness, and correct automatic responses. Agreed changes were later implemented by the IT Company. Equi-Commun was communicated and promoted through diverse communication strategies and multiple media channels between July 2017 and June 2019 (**Supplementary Table 2**). They consisted of presentations at scientific conferences; print media articles in equine magazines; distribution of flyers in equine clinics; e-mails sent to participants of the online survey to inform about the launch of Equi-Commun, to the Swiss veterinary faculty staff, and to veterinarians *via* the Equinella newsletter; and regular social media performance *via* Equi-Commun Facebook page.

Qualitative Interviews

To assess potential reasons for the equine owners' lack of compliance toward Equi-Commun, we conducted semi-structured qualitative phone interviews. An interview guideline was drafted according to the recommendations of Helfferich (39) and based on previous knowledge collected through the online questionnaire. Interview questions focused on capturing the knowledge and understanding of equine owners in regard to CBS and the CBS tool Equi-Commun, how they came in contact with it, reasons why they did not use Equi-Commun as well as reasons they thought why other equine owners did not use Equi-Commun, and what they recommended for promoting Equi-Commun successfully (**Table 2**). The study population for the interviews was recruited in two steps. First, equine owners who voluntarily left their e-mail-address during online survey in July 2018 ($n = 561$) were contacted per e-mail and invited to participate in a phone interview. As a motivation for participation, a voucher from an equine tack shop (CHF 50.-) was offered. Within 11 days, 108 equine owners indicated their interest. Second, of this subpopulation, 10 equine owners were randomly selected. The phone interviews were conducted in November 2019 and recorded digitally with prior oral consent from the interviewees. The interview time lasted on average for 15 min. The recordings were digitally transcribed verbatim. The transcripts were analyzed using the qualitative data analyzing software MAXQDA2020 Analytics Pro (VERBI Software, Berlin, Germany) applying an inductive open coding approach. The inductive open coding was conducted by reading the transcripts and selecting text parts related to a certain topic mentioned by the interviewee. This approach was repeated for all transcripts, and similar textual context among different interviewee transcripts was assigned to the same code. Matching certain transcript parts to codes was repeated until all transcripts were analyzed and no new codes were identified. Conducting the interviews, transcription and coding was done by one researcher for all interviews to ensure a homogeneous view on the complete study material. For the purpose of this publication, quotes were translated from German to English and adjusted for better understanding, if grammatically necessary.

TABLE 2 | Interview questions asked to equine owners during semi-structured telephone interviews on their knowledge and attitude toward Equi-Commun and on reporting clinical signs of their equine.

Interview questions
1) What do you know about Equi-Commun and what do you think about this platform?
2) How did you come in contact with Equi-Commun?
3) Do you feel informed about Equi-Commun?
4) Do you see any benefits in Equi-Commun? If not, why?
5) What are reasons for equine owners not reporting clinical signs of their equine?
6) Did you report any clinical signs? If not, why?
7) Do you have a suggestion what could be done differently or better for promoting Equi-Commun?

RESULTS

Online Survey

Response Rate and Demography of the Study Population

We received 1,078 completed questionnaires, leading to a response rate of 14.4%. The characteristics of the study population are presented in **Table 1**. The majority (57.3%) of the equine of the respondents were stated to be located in the cantons (states of Switzerland) of Bern, Zurich, Vaud, and Aargau (**Supplementary Figure 2**), matching with the spatial distribution of the equine population in Switzerland (40). The total number of equine owned by all respondents together resulted in 2,584 animals, with a median of two equine per respondent [range: 0–50, interquartile range (IQR): 1–3]. The median number of equine on the premises where the respondent's equine is stabled was 15 (range: 1–140, IQR: 5–26). The majority (55.5%, $n = 598$) of the equine owners transport their equine to other locations. The two most frequently selected reasons for transporting equine were attending a competition (61.7%, $n = 369$) and taking riding lessons (55.4%, $n = 331$).

Frequency of Observed Clinical Signs

All 1,078 respondents reported to have observed in total 17,016 clinical signs among their own equine and/or the equine on their premises during the last 12 months. The median number of clinical signs observed per respondent was 4 (range 0–340, IQR: 1–11). The most common observed clinical signs were pruritus (29.3%), respiratory signs (23.5%), lameness (19.1%), and diarrhea (14.5%) (**Supplementary Figure 3**). Overall, respondents contacted a veterinarian in 14.2% of the cases after observing clinical signs, with a median of 1 per respondent (range 0–60, IQR: 0–3) over the last 12 months.

MCA and Hierarchical Clustering of Factors Influencing Equine Owners' Perception and Attitude Toward CBS

The MCA and hierarchical clustering revealed three attitude clusters among the respondents with 41.4% ($n = 446$) of the respondents categorized to the highly positive attitude cluster, 52.2% ($n = 563$) to the moderately positive attitude cluster, and 6.4% ($n = 69$) to the negative attitude cluster (**Supplementary Figures 4A–C**).

The highly positive attitude cluster ($n = 446$) was characterized by the majority of the respondents within this cluster having highly positive attitudes toward factors mentioned in all sub-questions of question 21 and strongly agreeing to all statements of question 22. Among all reasons not to report, respondents from this cluster most frequently (52.0%) selected the answer "I don't have concerns."

The moderately positive attitude cluster ($n = 563$) was characterized by the majority of the respondents having rather positive attitudes toward factors mentioned in all sub-questions of question 21 and rather agreeing to the statements of question 22. Among the reasons not to report, respondents of this cluster most frequently (42.0%) answered with concerns about privacy and data security.

The negative attitude cluster ($n = 69$) was characterized by the majority of the respondents having negative attitudes toward factors mentioned in all sub-questions of question 21 and strongly or rather disagreeing to the statements of question 22. In contrast, the majority within this cluster reported that "other reasons" (70.0%) was the main reason for non-reporting. General disinterest, the perception of reporting being highly time-consuming, and the perception that monitoring clinical signs is the responsibility of veterinarians were among the comments added as free text when selecting "other reasons" for not reporting.

Factors Influencing the Intentions Toward CBS

The majority (65.5%, $n = 707$) of the 1,078 respondents answered that they could certainly (12.5%, $n = 135$, "certainly yes"), presumably (26.4%, n = 285, "presumably yes"), or potentially (26.6%, n = 287, "maybe") see themselves reporting clinical observations of their equine (question 18, outcome variable *would report*). Approximately a third (34.5,%, $n = 371$) of the 1,078 respondents answered that they would not (8.4%, $n = 91$) or rather not (26.0%, $n = 280$) report clinical signs they observed.

TABLE 3 | Factors influencing equine owner's intentions to report to Equi-Commun, a community-based surveillance tool for equine health, resulting from a multivariable logistic regression analysis are presented.

Factors	Levels	*p*-Value	OR (95% CI)
Language	German	–	Ref.
	French	<0.001	2.31 (1.45–3.74)
	Italian	0.095	10.19 (0.89–278.42)
Profession	Human health field	–	Ref.
	Working with equine	0.061	0.52 (0.26–1.02)
	Animal health field	0.022	0.32 (0.12–0.84)
	Farming	0.005	0.36 (0.18–0.72)
	Other profession	0.432	0.79 (0.43–1.42)
	I prefer not to say	0.002	0.31 (0.15–0.64)
Attitude cluster	Moderately positive attitude cluster	–	Ref.
	Highly positive attitude cluster	<0.001	11.29 (7.39–17.76)
	Negative attitude cluster	<0.001	0.13 (0.05–0.30)

In the univariate logistic regression models, the variables *age*, *type of ownership*, *type of premises*, *profession*, *gender*, *language*, and *attitude cluster* were associated with a $p < 0.2$ with the outcome *would report*. The final multivariable logistic regression model indicated three significant independent variables, *language*, *attitude cluster*, and *profession* (**Table 3**). *French-speaking* compared with *German-speaking* respondents had an odds ratio of 2.31 (95% CI: 1.45–3.74) of being associated with the outcome of having positive intentions to use CBS and Equi-Commun. The odds of respondents belonging to the highly positive *attitude cluster* and negative *attitude cluster* were 11.29 (95% CI: 7.39–17.76) and 0.13 (95% CI: 0.05–0.30), respectively, in regard to their intention to use CBS compared with moderately positive *attitude cluster*. Furthermore, respondents with the *profession farmer* (OR: 0.36, 95% CI: 0.18–0.72), those with a profession related to the field of *animal health* (OR: 0.32, 95% CI: 0.12–0.84) or respondents who did not provide their profession (OR: 0.31, 95% CI: 0.15–0.64) reported to have significantly lower intentions to report clinical signs of their animals than respondents working in the human health field.

The CBS Tool Equi-Commun

Equi-Commun was technically functioning without issues after its launch on October 22, 2018. Until December 31, 2019, Equi-Commun received four reports by three unique users (**Supplementary Table 3**). These consisted of two cases of lameness, one case of colic, and one case of pastern dermatitis. None of the reports were explicitly related to infectious diseases or its suspect. None of the users registered to the system, instead they submitted their reports without registering. Because of its non-use, the Equi-Commun reporting tool website was inactivated at the end of December 2019.

Qualitative Phone Interviews

Fifteen codes were identified during the analysis of the transcripts (**Table 4**). Among the 10 interviewed participants, all stated to have a positive attitude toward Equi-Commun. An example for

TABLE 4 | Codes created by intuitive coding using MAXQDA2020 Analytics Pro based on transcripts of semi-structured qualitative interviews among 10 equine owners regarding their perception of Equi-Commun (EC), definition of codes, and an example quote from the transcripts.

Code name	Explenation of code theme	Quote examples from transcripts
Positive attitude toward EC	Participant had a positive attitude toward EC	"…when I read some of it, I thought, yes, that still sounds exciting, I think it's a good thing. When knowledge, is acquired and the knowledge is later tried to be spread."
Lack of memory	Participants could not or just partly remember the concept of EC	"Honestly, I know practically nothing about it [Equi-Commun]." "I don't remember it. It's a bit embarrassing because I really didn't know what Equi-Commun actually is. Yeah, no, I usually remember things like that, but obviously it didn't stick."
Need of active information	Participants express their opinion for the need of more active information about EC	"I would do Facebook marketing with short, concise educational material written in the style of the equestrian revue or horse magazines. And I would do this seasonally on horse topics on things that are currently topics, now with the hay quality in autumn, with Cushing's [Cushing disease] or with worms etc."
Found information through the internet	Participants got the information about EC through the internet by searching themselves or by coincidence	"I found this [Equi-Commun] on the Internet by accident."
Suggestion for non-compliance: missing medical knowledge	Participants think that missing knowledge about equine in general and/or in the medical field is a reason for missing compliance	"Yes I think they [other equine owners] are afraid to report, or to report something wrong, or to interpret something that is wrong and that it is better that some professional does it."
Suggestion for non-compliance: equine are healthy	Participants think that owners did not comply with the system because their equine were healthy	"So when I talk about me now, I have a horse that has no medical problem. Maybe they (persons who did not report) are all people who had extremely healthy horses."
Suggestion for non-compliance: anxiety	Participants think that the anxiety of consequences due to notifying clinical signs might be a reason of missing compliance	"I believe that fears is there." "And I also think there is fear that you could be convicted of something." "Fear of being reported. It's quite possible that people will find it. Am I registered? Can I then perhaps no longer go and finish the (riding) course? And I always think it's something like that."
Suggestion for non-compliance: lack of awareness about EC	Participants think that lack of awareness about EC among other equine owners could be a reason for missing compliance	"I might be able to tell you what happened to me. I filled out the survey once and then I kind of really forgot about it. I didn't realize anymore that something like this [Equi-Commun] existed and that you should do something about it." "If then afterwards the horse has something that you probably don't even think about that you could/should report it… Yes, you might be a bit stressed afterwards and yes, your thoughts tend to be somewhere else."
Did not understand the concept of CBS	Participants did not know the differences or the meaning of the terms clinical signs and diseases	Answer to the question if participant observed clinical signs after having explained the concept of EC: "For what disease again? Or in general?" "Yeah, the EHV-4, I could have reported it."
Well informed	Participants found themselves well informed about EC	Answer to the question how the participant found the information provided about EC:"…but it was quite informative there."
Limited interest	The interest of the participant in EC was limited	"I got that in a survey once, but I didn't follow it up." "It simply hasn't had any relevance for me lately or hasn't become relevant yet. Now I have forgotten about it [Equi-Commun] ever since."
Lacking information	The information provided about EC was perceived as lacking	"Because if you don't hear anything or have to search God knows where on the Internet until you can read up, I find it rather difficult."
Doubts	Participants had doubts about the added value of EC	"But I then asked myself how developments can be mapped in a timely manner. So if you write something down or make an entry, is it simply statistically empirically afterwards or can you really use it directly and promptly? That was not so clear to me… That's why I'm not sure if it (Equi-Commun) will lead to a flood of information for what is expected to result as an output later."
Good memory	Participant remembered EC well and was correctly informed about its aims	"I understand that Equi-Commun invites horse owners in particular to report any incidence of disease occurrences, especially those that are transmissible. And I have understood that Equinella is looking for this, especially from veterinarians."
Misinformed	Participant was wrongly informed about EC	"So, I imagined that it is simply about the relationship between man and horse, what is good for the horses, what is bad for the horses. Something like that."

quote for the code "Positive attitude toward Equi-Commun" was: "... when I read some of it, I thought, yes, that still sounds exciting, I think it's a good thing. When knowledge is acquired and the knowledge is later tried to be spread."

Only few of the respondents mentioned limited interest in the tool. Some respondents stated that they previously felt well-informed about Equi-Commun, yet only few correctly remembered the aim and use of the CBS tool Equi-Commun. An example quote for the code "Misinformed" was: "So, I imagined that it (Equi-Commun) is simply about the relationship between man and horse, what is good for the horses, what is bad for the horses. Something like that." This quote from one of the respondents points toward the lack of understanding that Equi-Commun was designed as a CBS tool to report clinical signs.

Several respondents mentioned to have gathered information about Equi-Commun over the internet and that they came across Equi-Commun randomly while searching for equine health content on the web. Some respondents further mentioned that they perceived active and repetitive information as necessary to improve compliance with the platform. To the question on what reasons other equine owners might have had for not reporting their observations to Equi-Commun, respondents mentioned the following ideas: (a) lack of awareness about Equi-Commun, (b) a possible anxiety of creating a negative impact if clinical signs were reported, (c) missing clinical knowledge among the equine owners regarding general issues about equine and medical understanding, and (d) that their equine were healthy, and thus they were not able to report health issues. An example quote for the code "Suggestion for non-compliance: lack of awareness about Equi-Commun" was: "I might be able to tell you what happened to me. I filled out the survey once and then I kind of really forgot about it. I didn't realize anymore that something like this (Equi-Commun) existed and that you should do something about it."

DISCUSSION

The present study is the first attempt at determining the potential and challenges of CBS within the Swiss equine community. Additionally, this is the first study describing the process of establishing and disseminating a CBS tool for equine surveillance. Although the aim of Equi-Commun was to assess the benefit of surveillance data derived from a CBS approach compared with already existing equine health surveillance data, this aim was not achieved in the current project, as Equi-Commun received only four reports for the duration it was online.

The success of a CBS system is dependent on the perceived need of the community toward generating surveillance information. El Allaki et al. argued in their theoretical work on health surveillance theory that the initiation of a surveillance process requires three steps: (i) a dissatisfaction regarding the current (health) situation, (ii) a need for knowledge and/or time-dependent information, and (iii) some level of motivation to eliminate the dissatisfaction and to approach the information need on the population health status (41). Applying this concept to the equine CBS tool we have strived to implement, equine owners should have recognized and perceived a certain dissatisfaction regarding their equine's health and/or their surveillance in order to show compliance to a CBS approach. Or in other words, only if there was a strong enough perceived need for CBS in the Swiss equine community, such a system would have likely been successful. Indeed, the idea of Equi-Commun was created after stakeholders from the Swiss equine industry clearly stated their interest in being actively involved in the surveillance of equine health during a Swiss equine health network conference in 2016. Build on that, while our study has not directly assessed the dissatisfaction of equine owners nor the perceived need for CBS, it did assess the intentions of Swiss equine owners toward CBS by making use of an online survey. As it was found, the majority of the respondents (65.5%, $n = 707$) answered that they could see themselves reporting clinical signs. These aspects together could be regarded as a promising prerequisite for the success of a CBS approach, and we therefore expected to receive more interest in and reports submitted to Equi-Commun. However, this was not the case.

Possible explanations for this non-use of Equi-Commun can be found in disciplines investigating the complexity of human behavior. According to the Theory of Planned Behavior (TPB), a specific human behavior related to a certain planned action is a product of humans' "intention" to carry out this planned action, their "attitudes" (i.e., values, priorities) toward the action, "social norms" (i.e., external expectations placed upon them), and their "perceived behavioral control" (i.e., their perceived ability to put actions of their choice into effect) in regard to the action (42, 43). In our study, we investigated the behavior of people, i.e., whether they used the CBS tool, by observing the reports submitted to Equi-Commun (**Figure 1**). On the other hand, we investigated the intention to report to Equi-Commun and the attitudes that may drive this intention through the online survey. The majority (65.5%) stated that they intend to report or at least maybe report to a tool, such as Equi-Commun. However, selection bias is expected to be prevalent for the online survey, as it is the case in most voluntary questionnaire-based studies (44, 45), which may have led to an overestimation of the equine community's rather positive intention. In particular, respondents have possibly reflected on the equine communities and their role in disease surveillance in a more positive way than they actually thought about it. The concept of responding to a possibly moral or ethical question in a way that an individual thinks the society expects them to respond is described in the so-called social desirability bias (44, 46). In addition, we assessed the attitude toward CBS and the intention to use it through the respondent's self-reflection on a description of the yet to be established Equi-Commun (**Supplementary Material 1**, section C, question 16). Hence, respondents were not able to reflect on previous experiences directly, yet only on their reflection on a hypothetical case scenario description of a CBS tool. Furthermore, in the qualitative telephone interviews conducted, after it was apparent that Equi-Commun would not be used, we again observed a positive perception toward the CBS tool, with all interviewees responding to clearly see a benefit in Equi-Commun. However, the selection bias in this group is even more expected, as participants of the telephone interviews were selected from the

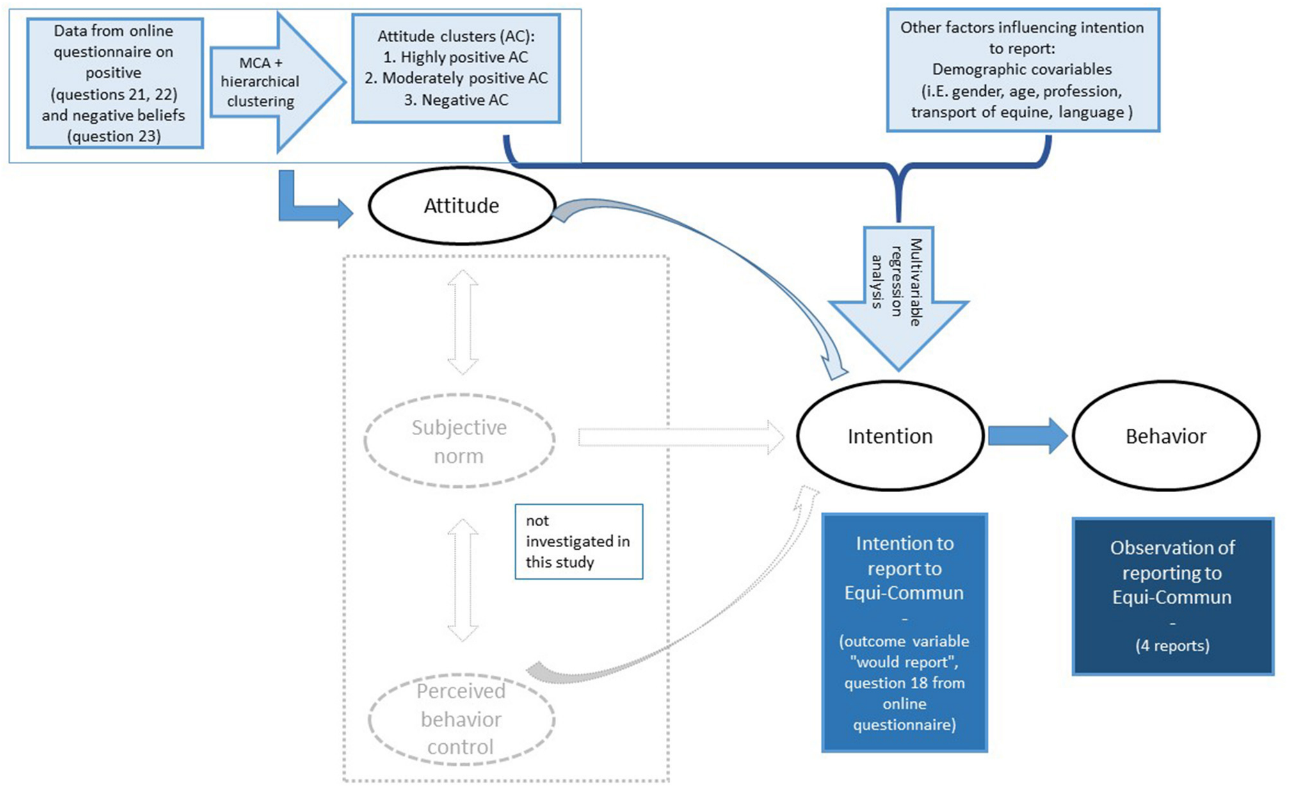


FIGURE 1 | Framework of the Theory of Planned Behavior (TPB) by Ajzen (43) adapted to investigate factors influencing the intention and observed behavior to report to the CBS tool Equi-Commun.

pool of online survey respondents that left their e-mail address voluntarily at the end of the questionnaire, in order to be updated in regard to Equi-Commun developments. In particular, later exploration of the qualitative interview participants after conducting the MCA revealed that 4 of 10 interviewees were assigned to the highly positive attitude cluster, whereas 6 were assigned to the rather positive attitude cluster. No interview was conducted with persons from the negative attitude cluster. Thus, saturation of perspectives among equine owners with different attitudes toward CBS could not be reached. It is likely that telephone interviewees, similar to the respondents of the online questionnaire, represent the more interested equine owners with positive attitudes toward CBS, than average.

We investigated the factors collected during the questionnaire as drivers of the observed intention of respondents to submit reports to Equi-Commun. Equine owners categorized in the highly positive attitude cluster were nearly 12 times more likely to have a positive intention toward reporting to Equi-Commun than individuals from the moderately positive attitude cluster. Interestingly, the respondents belonging to the respective attitude cluster answered to all sub-questions in a similar way, suggesting that they either fully support a system, such as Equi-Commun (highly positive attitude cluster), or deny it (negative attitude cluster), whereas the moderately positive attitude cluster is somewhere in the middle. This might indicate that type of incentives for reporting clinical signs is not crucial (e.g., by receiving information material, profit from the own equine health diary, getting feedback from the system about the health status in the Swiss or regional equine population)—either persons have a positive attitude, therefore see certain incentives and would like to profit from all benefits, or they have a negative attitude toward the tool, therefore prefer not to report. The same picture was apparent in regard to the perception on how CBS would help to improve the health of the own equines, the equines from the premises, the equines in the region, or all equines in Switzerland. Again, the respondent supports either most of these statements or almost none. This clear separation of the respondents leaves little room for motivating the respondents seeing no benefit at all (individuals from the negative attitude cluster)—fortunately, this cluster consists of only 6.4% of the population.

We have also revealed that respondents who classified themselves as farmers and those working in the animal health field (including veterinarians) are less likely to report to a CBS tool, such as Equi-Commun, than equine owners working in the human health field. This could be due to the negative perception of these professional groups toward collecting health data in addition to the currently mandatory data documenting needs (42, 47). In light of existing surveillance, monitoring, control programs, and respective documentation responsibilities, the burden for committing to an additional surveillance system, such as a CBS tool, is possibly higher for equine owners who are part of the farming and animal health sectors than for equine owners of other professions. Crosslinking of existing health data might therefore be of upmost importance to disburden professional animal owners from data reporting. On the other hand, engaging equine owners from these health fields might bring more potential for a CBS tool, because they are expected to be able to deliver better quality and higher quantity data than other professions owning few animals.

Finally, we observed that the odds were 2.3 times higher for the intention to report to Equi-Commun in French-speaking equine owners than in German-speaking owners. Such differences in attitudes along language borders within Switzerland have already been reported in different fields. For example, acceptance of replacing nuclear power plants was lower among French-speaking Swiss individuals than among German-speaking (48); or the agreement of Swiss physicians toward end-of-life decisions by use of lethal drugs was higher among French-speaking than among German- and Italian-speaking medicals (49). Such differences based on the language-use and language regions are likely due to cultural differences, acceptance of certain habits, and overall positioning in regard to health and health-related topics. Targeted project communications and information dissemination should therefore take them into account.

Within our study, we were able not only to investigate the attitudes and intention of the equine owners in regard to CBS but also to test their actual behavior. The actual behavior of interest in this contexts is defined as the reporting of clinical signs to Equi-Commun. With the majority of the respondents having stated positive intention toward CBS and only four reports recorded in Equi-Commun, we clearly observed a so-called intention-behavior gap. This concept describes the discrepancies between human intention to perform a certain behavior and them acting accordingly and has found particular interest in the research of medical and lifestyle behavior of patients within the health sector (50–52). Evidence shows that intentions get translated into actions in only about half of all cases (51). Obstacles influencing the intention-behavior gap can be divided into three main categories: getting a new tool started (e.g., in our case, setting the intention to report clinical signs), keeping it ongoing (e.g., keeping informed about Equi-Commun), and reach the goal (e.g., the actual act of reporting to Equi-Commun) (51). Possible explanations for the observed intention-behavioral gap may be found in each of these three obstacles. However, even though critically important, elaborating the complexity of equine owners' intentions and how they translate it into behavior have to be deferred to a next study investigating these concepts and how these apply to community-based animal health surveillance.

Engaging stakeholders in CBS is complex and requires their active involvement starting by assessing the need toward CBS as well as throughout the implementation process. In their conceptual study on fish farmers' potential in aquatic syndromic surveillance, Brugere et al. emphasized that the authority of veterinarians and diagnostic laboratories must be extended to include farmers (53). According to the authors, farmers should be acknowledged as the starting point of disease surveillance, with equal power and responsibility. Therefore, including relevant stakeholder's knowledge, opinions, and needs as well as methods and tools to ensure such inclusive processes must be guaranteed for a successful CBS, already during its conceptualization. Within our study although we attempted to investigate the wide equine community's attitude toward a CBS tool through the online questionnaire, members of the community were not included in the development of the tool. We would have possibly been more active in uncovering the underlying dynamics in equine owner's surveillance behavior holistically and continuously by applying transdisciplinary approaches to co-constructing CBS in the Swiss equine community. As an example, in the beginning phase of the project, regular stakeholder workshops with equine owners could have been organized to start assessing the overall attitude toward CBS and to better assess its needs in this community. Such workshops should be accompanied by experts from social sciences, such as sociology, psychology, and anthropology (54, 55). Intervention mapping, a theory- and evidence-based framework providing a systematic and stepwise approach toward planning health interventions, may have been other concepts and tools worth to be consulted for planning, developing, and implementing a CBS system (56). Intervention mapping is grounded in community-based participatory research methods to ensure that the intervention matches priority population needs, and thus may have been a useful tool to investigate equine owners' underlying thought processes and dynamics in regard to CBS.

One of the most relevant shortcomings of successfully implementing a CBS system may probably lie in project dissemination, communication, and marketing. An effective CBS approach requires personal staff dedicated to manage the project, continuously contact, inform and support community members in collecting data, maintain a database, analyze and visualize data, and disseminate analysis outcomes (57). Within the scope of our study, we have adapted several strategies to disseminate Equi-Commun effectively (**Supplementary Table 2**). The qualitative interviews, however, revealed that even though equine owners felt well-informed, most of them could not remember Equi-Commun and its objectives correctly. This suggests that effective project communication has failed. In a study in northern Australia and Papua New Guinea, researchers investigated factors influencing the acceptability and value of CBS for dog rabies (58). The authors revealed that verbal communication, such as direct conversations, radio, and community meetings, was mentioned the strongest, whereas social media posts (depending on the region and age of community members) and print media were less likely to be valued by community members. A study conducted among Swedish dairy cattle farmers suggests that consistent, persistent, audience-tailored, benefit-revealing, and personal contact and communication between receivers and providers of data are key assets to a successful and continuous data collection (12, 20). Potential action points included oral and participatory information exchange during data collection, refresher training workshops for community-based animal health workers, or rural radio programs with disease information spread for cattle farmers (20). These experiences show how specific feedback operations must be to meet the exact needs of data providers in order to maintain compliance. In our study, we revealed that although information provided by the project management team during the communication phases was perceived as clear and understandable, it was not efficient and persistent enough to be remembered after 1 years' time. This demands for consistent, targeted and more frequent information campaigns. Profound trans- and interdisciplinary approaches for project communication and dissemination through the inclusion of equine owners and experts from social sciences, in addition to the veterinary epidemiologist and equine practitioner, could have substantially benefited the implementation of Equi-Commun. Researchers and surveillance practitioners planning to translate their CBS ideas to practice should make use of existing methodological frameworks and toolkits from the implementation science field, which encompasses the right tools for narrowing the gap between implementation in research settings and implementations of programs intended to be used in everyday practices (59). These have been approaches and methodologies not made use of during the implementation of Equi-Commun. However, when planning implementation strategies and more resource demanding interventions for setting up a CBS system, the benefit should be weighed in comparison with the necessary resources, such as personal, finances, and time. Even though CBS systems can be less material demanding than active surveillance system (e.g., continuous serological surveillance), certain "hidden" resources needed to set up and maintain the system have to be accounted for. In the case of CBS within the equine community in Switzerland, despite the given interest and potential of equine owners to observe clinical signs, the benefits of having CBS data as additional surveillance information would not have overweigh the efforts and resources required.

Furthermore, the relatively high level of equine health among the Swiss population was a potential reason for the equine owners' non-compliance to Equi-Commun. This was confirmed by interviewees of the qualitative survey mentioning their equine's good health as a reason for non-reporting of clinical signs. Although census studies on the health or diseases of the Swiss equine population are lacking, judging by the low number of official reports on notifiable infectious diseases–which encompassed only five cases of Salmonellosis and one case of Contagious Equine Metritis (CEM) within 1 year (07.14.2018–07.14.2019)–support the argument that at least critical equine infectious diseases are rare (60). Similarly, although a voluntary reporting system of non-notifiable diseases, and therefore not expected to be thoroughly representative of each disease event in the equine population, reports submitted to Equinella have also been rather low in number (34). On the other hand, respondents of the online questionnaire reported as a median to have observed four times clinical signs among their equine within a year. Additionally, respondents of the online questionnaire stated to have contacted a veterinarian in only 14.2% of all observed clinical cases. This is pointing toward that the information of a great majority of clinical signs observed by equine owners does not get forwarded to veterinarians in the first place. Therefore, in case Equi-Commun would be more present in the equine owners' mind, there is potential for reports in a CBS tool. It is noteworthy that the large majority of clinical signs observed (mostly pruritus, lameness, and respiratory signs) are not clearly related to infectious diseases. This suggests that while clinical signs of infectious diseases might be rather rarely observed, such related to non-infectious diseases may be used as a motivation of equine owners to record their animal's health diary, and as such promote CBS tools also for infectious disease. Nonetheless, the currently known good health status of equine in Switzerland does not urge the requirement of a CBS system as an addition to existing surveillance systems, particularly in terms of covering further infectious disease surveillance.

CONCLUSION

This study contributed to the little explored potential in equine owner's observations of clinical signs used for continuous surveillance of equine diseases, by assessing the equine owners' attitudes and intentions toward CBS and by developing and testing a CBS tool, named Equi-Commun. The intention of contributing to disease surveillance among equine owners is given, and equine owners detect health issues of their animals on average four times per year. However, we observed a clear intention-behavior gap, as the implemented CBS tool was not used among the equine owners. We here identified three critical, interlinked issues that may have led to the non-use of Equi-Commun within the Swiss equine community: (1) the need for surveillance within the community of interest must be given and should be assessed before implementing CBS; (2) the respective population under surveillance, here the equine, needs to show enough relevant clinical cases for equine owners to be able to maintain the memory of an existing tool and its possible use, and (3) targeted and high effort communication and management of the system is key for its success. While CBS relying only on lay animal owners could potentially provide a good proxy of timely surveillance data, complementary to existing surveillance systems, it is questionable whether the added value of generated surveillance knowledge is in balance with the efforts necessary to implement a successful system. With this study, we showcased both the potential and challenges of CBS in animal health, as this may be of relevance and guidance for similar future initiatives.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

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

AUTHOR CONTRIBUTIONS

RÖ designed and conducted the online questionnaire, co-worked on the conceptualization and implementation of Equi-Commun, conducted the information dissemination and management of Equi-Commun, supervised the qualitative interviews, conducted data analysis and wrote the first draft of the manuscript. SK conducted the qualitative interviews and applied qualitative analysis on them, as well as wrote parts of the manuscript. VV has helped to conceptualize and reviewed the online survey and qualitative interview questions, as well as helped to analyze the data. DH and FR-W have contributed to the conceptualization of Equi-Commun and the online survey. SD has designed the study and supervised all parts. All authors contributed to the data interpretation, manuscript revision, read, and approved the submitted version.

FUNDING

This study was funded by the Federal Food Safety and Veterinary Office of Switzerland with the grant number 1.17.09.

ACKNOWLEDGMENTS

The authors would like to thank all equine owners participating in this study and supporters for their efforts on distributing the information on Equi-Commun within their circles. We would further like to thank Ruth Hauser, working at the Federal Food Safety and Veterinary Offices, for her conceptual input to the surveys and Equi-Commun.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.641448/full#supplementary-material

REFERENCES

1. Dórea FC, Vial F. Animal health syndromic surveillance: a systematic literature review of the progress in the last 5 years (2011–2016). *Vet Med Res Reports.* (2016) 7:157–70. doi: 10.2147/VMRR.S90182
2. Hoinville LJ, Alban L, Drewe JA, Gibbens JC, Gustafson L, Häsler B, et al. Proposed terms and concepts for describing and evaluating animal-health surveillance systems. *Prev Vet Med.* (2013). 112:1–12. doi: 10.1016/j.prevetmed.2013.06.006
3. Bisdorff B, Schauer B, Taylor N, Rodríguez-Prieto V, Comin A, Brouwer A, et al. Active animal health surveillance in European Union Member States: gaps and opportunities. *Epidemiol Infect.* (2017) 145:802–17. doi: 10.1017/S0950268816002697
4. Tapprest J, Foucher N, Linster M, Laloy E, Cordonnier N, J-P Amat, et al. Resumeq: a novel way of monitoring equine diseases through the centralization of necropsy data. *Front Vet Sci.* (2019) 6:135. doi: 10.3389/fvets.2019.00135
5. Küker S, Faverjon C, Furrer L, Berezowski J, Posthaus H, Rinaldi F, et al. The value of necropsy reports for animal health surveillance. *BMC Vet Res.* (2018) 14:191. doi: 10.1186/s12917-018-1505-1
6. Muellner P, Muellner U, Gates MC, Pearce T, Ahlstrom C, O'Neill D, et al. Evidence in practice – a pilot study leveraging companion animal and equine health data from primary care veterinary clinics in New Zealand. *Front Vet Sci.* (2016) 3:116. doi: 10.3389/fvets.2016.00116
7. Faverjon C, Andersson MG, Decors A, Tapprest J, Tritz P, Sandoz A, et al. Evaluation of a multivariate syndromic surveillance system for west nile virus. *Vector-Borne Zoonotic Dis.* (2016) 16:382–90. doi: 10.1089/vbz.2015.1883
8. Gibbens JC, Robertson S, Willmington J, Milnes A, Ryan JBM, Wilesmith JW, et al. Use of laboratory data to reduce the time taken to detect new diseases: VIDA to FarmFile. *Vet Rec.* (2008) 162:771–6. doi: 10.1136/vr.162.24.771
9. Doherr MG, Audigé L. Monitoring and surveillance for rare health-related events: a review from the veterinary perspective. *Philos Trans R Soc B Biol Sci.* (2001) 356:1097–106. doi: 10.1098/rstb.2001.0898
10. Carrat F, Sahler C, Rogez S, Leruez-Ville M, Freymuth F, Le Gales C, et al. Influenza burden of illness: estimates from a national prospective survey of household contacts in France. *Arch Intern Med.* (2002) 162:1842–8. doi: 10.1001/archinte.162.16.1842
11. Espetvedt M, Lind A-K, Wolff C, Rintakoski S, Virtala A-M, Lindberg A. Nordic dairy farmers' threshold for contacting a veterinarian and consequences for disease recording: mild clinical mastitis as an example. *Prev Vet Med.* (2013) 108:114–24. doi: 10.1016/j.prevetmed.2012.07.014
12. Mörk M, Lindberg A, Alenius S, Vågsholm I, Egenvall A. Comparison between dairy cow disease incidence in data registered by farmers and in data from a disease-recording system based on veterinary reporting. *Prev Vet Med.* (2009) 88:298–307. doi: 10.1016/j.prevetmed.2008.12.005
13. Marquet RL, Bartelds AIM, Van Noort SP, Koppeschaar CE, Paget J, Schellevis FG, et al. Internet-based monitoring of influenza-like illness (ILI) in the general population of the Netherlands during the 2003-2004 influenza season. *BMC Public Health.* (2006) 6:242. doi: 10.1186/1471-2458-6-242
14. Guerra J, Acharya P, Barnadas C. Community-based surveillance: a scoping review. *PLoS ONE.* (2019) 14:e0215278. doi: 10.1371/journal.pone.0215278
15. Guerra J, Bayugo Y, Acharya P, Adjabeng M, Barnadas C, Bellizzi S, et al. A definition for community-based surveillance and a way forward: results of the who global technical meeting, france, 26 to 28 june 2018. *Euro surveill.* (2019) 24:1800681. doi: 10.2807/1560-7917.ES.2019.24.2.1800681
16. Ndiaye SM, Quick L, Sanda O, Niandou S. The value of community participation in disease surveillance: a case study from Niger. *Health Promot Int.* (2003) 18:89–98. doi: 10.1093/heapro/18.2.89
17. Dil Y, Strachan D, Cairncross S, Korkor AS, Hill Z. Motivations and challenges of community-based surveillance volunteers in the Northern Region of Ghana. *J Community Health.* (2012) 37:1192–8. doi: 10.1007/s10900-012-9569-5
18. Norwegian Red Cross. *First Covid-19 Case in Somaliland Detected through CBS.* (2020) Available online at: https://uploads-ssl.webflow.com/5d1f301c241e1b056c29ecc6/5e99ad4064d69431fae937a8_5e878d25f99d7c6fa267961c_cbs-covid-19-so_45425167-p-800.png (accessed June 8, 2020).
19. Catley A, Alders RG, Wood JLN. Participatory epidemiology: approaches, methods, experiences. *Vet J.* (2012) 191:151–60. doi: 10.1016/j.tvjl.2011.03.010
20. Mariner J, Catley A, Zepeda C. *The Role of Community-Based Programmes and Participatory Epidemiology in Disease Surveillance and International Trade.* Montpellier (2002). Available online at: https://pdfs.semanticscholar.org/ef10/81a7697bd6383342c9ada25e29f67184bad3.pdf (accessed August 31, 2018).
21. Pollard D, Wylie CE, Newton JR, Verheyen KLP. Incidence and clinical signs of owner-reported equine laminitis in a cohort of horses and ponies in Great Britain. *Equine Vet J.* (2019) 51:587–94. doi: 10.1111/evj.13059
22. Smolinski MS, Crawley AW, Olsen JM, Jayaraman T, Libel M. Participatory disease surveillance: engaging communities directly in reporting, monitoring, and responding to health threats. *JMIR Public Heal Surveill.* (2017) 3:e62. doi: 10.2196/publichealth.7540
23. Allport R, Mosha R, Bahari M, Swai E, Catley A. *The Use of Community-Based Animal Health Workers to Strengthen Disease Surveillance Systems in Tanzania.* (2005). Available online at: https://pdfs.semanticscholar.org/9f39/888e9a5eb2f6b2dae06bcac885107d3b9862.pdf (accessed August 31, 2018.)
24. Kongelf A, Bushby RM, Gejibo S, Kaur G, Tingberg T. Technology volunteerism - the red cross' approach to developing a digital community based surveillance tool for early detection of diseases with epidemic potential. *Int J Infect Dis.* (2019) 79:26. doi: 10.1016/j.ijid.2018.11.078
25. Struchen R, Reist M, Zinsstag J, Vial F. Investigating the potential of reported cattle mortality data in Switzerland for syndromic surveillance. *Prev Vet Med.* (2015) 121:1–7. doi: 10.1016/j.prevetmed.2015.04.012

26. Bronner A, Hénaux V, Fortané N, Hendrikx P, Calavas D. Why do farmers and veterinarians not report all bovine abortions, as requested by the clinical brucellosis surveillance system in France? *BMC Vet Res.* (2014) 10:93. doi: 10.1186/1746-6148-10-93
27. Mardones FO, Redding L, Hardefeldt L, C Stärk KD, Pinto Ferreira J, Høg BB, et al. Monitoring of farm-level antimicrobial use to guide stewardship: overview of existing systems and analysis of key components and processes. *Front Vet Sci.* (2020) 1:540. doi: 10.3389/fvets.2020.00540
28. Cole FL, Hodgson DR, Ried SWJ, Mellor DJ. Owner-reported equine health disorders: results of an Australia-wide postal survey. *Aust Vet J.* (2005) 83:490–5. doi: 10.1111/j.1751-0813.2005.tb13301.x
29. Ireland JL, Wylie CE, Collins SN, Verheyen KLP, Newton JR. Preventive health care and owner-reported disease prevalence of horses and ponies in Great Britain. *Res Vet Sci.* (2013) 95:418–424. doi: 10.1016/j.rvsc.2013.05.007
30. Legrand LJ, Pitel PY, Marcillaud-Pitel CJ, Cullinane AA, Courouсé AM, Fortier GD, et al. Surveillance of equine influenza viruses through the RESPE network in France from November 2005 to October 2010. *Equine Vet J.* (2013) 45:776–83. doi: 10.1111/evj.12100
31. *VigiRESPE.* (2020). Available online at: https://www.vigirespe.net/ (accessed June 3, 2020).
32. Valon F, Marcillaud-Pitel C, Fortier G, Chaffaux S, Tritz P, D'Ablon X, et al. Le RESPE: réseaud'épidémiosurveillance en pathologie équine. *Bull épidémiologique, Santé Anim Aliment.* (2012) p. 16. Available online at: https://be.anses.fr/sites/default/files/BEP-mg-BE49-art6.pdf (accessed June 3, 2020).
33. Wohlfender-Remy F, Struchen R, Graubner C, Balmer S, Hadorn D. Re-launch of Equinella: a web-based equine disease reporting and information platform. *J Equine Vet Sci*. 39:S17. doi: 10.1016/j.jevs.2016.02.035
34. Özçelik R, Graubner C, Remy-Wohlfender F, Dürr S, Faverjon C. Evaluating 5.5 Years of equinella: a veterinary-based voluntary infectious disease surveillance system of equines in Switzerland. *Front Vet Sci.* (2020) 7:327. doi: 10.3389/fvets.2020.00327
35. Struchen R, Hadorn D, Wohlfender F, Balmer S, Süptitz S, Zinsstag J, et al. Experiences with a voluntary surveillance system for early detection of equine diseases in Switzerland. *Epidemiol Infect.* (2016) 144:1830–6. doi: 10.1017/S0950268816000091
36. *Agate.* (2020) Available online at: https://www.blw.admin.ch/blw/de/home/politik/datenmanagement.html (accessed October 19, 2020).
37. R Core Team. *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing. (2019) Available online at: https://www.r-project.org/ (accessed May 15, 2020).
38. Husson F, Josse J, Le S, Maintainer JM. *Package "FactoMineR" Title Multivariate Exploratory Data Analysis and Data Minin*g. (2020). Available online at: http://factominer.free.fr (accessed May 14, 2020).
39. Helfferich C. Leitfaden- und Experteninterviews. In: Baur N, Blasius J, editors. Handbuch Methoden der empirischen *Sozialforschung*. Wiesbaden: Springer VS (2019). doi: 10.1007/978-3-658-21308-4_44
40. Equine population distribution Switzerland. (2020) Available online at: https://tierstatistik.identitas.ch/de/map-equids-canton.html (accessed September 14, 2020).
41. El Allaki F, Bigras-Poulin M, Michel P, Ravel A. A population health surveillance theory. *Epidemiol Health.* (2012) 34:e2012007. doi: 10.4178/epih/e2012007
42. Alarcon P, Wieland B, Mateus AL, Dewberry C. Pig farmers' perceptions, attitudes, influences and management of information in the decision-making process for disease control. *Prev Vet Med.* (2013) 116:223–42. doi: 10.1016/j.prevetmed.2013.08.004
43. Ajzen I. *The Theory of Planned Behavior*, ed. Amherst: University of Massachusetts at Amherst Academic Press. Inc. (1991). doi: 10.1016/0749-5978(91)90020
44. Thea F van de Mortel. *Faking It: Social Desirability Response Bias in Selfreport Research*. Available online at: http://www.ajan.com.au/Vol27/AJAN_27-3.pdf#page=45 (accessed April 20, 2021).
45. Bethlehem J. Selection Bias in Web Surveys. *Int Stat Rev.* (2010) 78:161–88. doi: 10.1111/j.1751-5823.2010.00112.x
46. Edwards AL. *The Social Desirability Variable in Personality Assessment and Research*. Dryden Press (1957). Available online at: https://psycnet.apa.org/record/1958-00464-000 (accessed April 20, 2021).
47. Hammed NS, Owis MI. An integrated health monitoring system. *Int Conf Adv Biomed Eng ICABME.* (2015) 9874732:197–200. doi: 10.1109/ICABME.2015.7323286
48. Keller C, Visschers V, Siegrist M. Affective imagery and acceptance of replacing nuclear power plants. *Risk Anal.* (2012) 32:464–77. doi: 10.1111/j.1539-6924.2011.01691.x
49. Fischer F. Swiss doctors' attitudes towards end-of-life decisions and their determinants: a comparison of three language regions. *Swiss Med Wkly.* (2006) 136:370–6.
50. Sheeran P. Intention—behavior relations: a conceptual and empirical review. *Eur Rev Soc Psychol.* (2002) 12:1–36. doi: 10.1080/14792772143000003
51. Sheeran P, Webb TL. The intention-behavior gap. *Soc Personal Psychol Compass.* (2016) 10:503–18. doi: 10.1111/spc3.12265
52. Faries MD. Why we don't "Just Do It": understanding the intention-behavior gap in lifestyle medicine. *Am J Lifestyle Med.* (2016) 10:322–29. doi: 10.1177/1559827616638017
53. Brugere C, Onuigbo DM, Morgan KL. People matter in animal disease surveillance: Challenges and opportunities for the aquaculture sector. *Aquaculture.* (2017) 467:158–69. doi: 10.1016/j.aquaculture.2016.04.012
54. Paul MC, Figuié M, Kovitvadhi A, Valeix S, Wongnarkpet S, Poolkhet C, et al. Collective resistance to HPAI H5N1 surveillance in the Thai cockfighting community: insights from a social anthropology study. *Prev Vet Med.* (2015) 120:106–14. doi: 10.1016/j.prevetmed.2015.02.021
55. Jerolmack C. Who's worried about turkeys? How 'organisational silos' impede zoonotic disease surveillance. *Sociol Health Illn.* (2013) 35:200–12. doi: 10.1111/j.1467-9566.2012.01501.x
56. Fernandez ME, Ruiter RAC, Markham CM, Kok G. Intervention mapping: theory- and evidence-based health promotion program planning: perspective and examples. *Front Public Heal.* (2019) 7:209. doi: 10.3389/fpubh.2019.00209
57. Bonney R, Cooper CB, Dickinson J, Kelling S, Phillips T, Rosenberg K V, et al. Citizen science: a developing tool for expanding science knowledge and scientific literacy. *Bioscience.* (2009) 59:977–84. doi: 10.1525/bio.2009.59.11.9
58. Brookes VJ, Kennedy E, Dhagapan P, Ward MP. Qualitative research to design sustainable community-based surveillance for rabies in Northern Australia and Papua New Guinea. *Front Vet Sci.* (2017) 4:19. doi: 10.3389/fvets.2017.00019
59. Meyers DC, Katz J, Chien V, Wandersman A, Scaccia JP, Wright A. Practical implementation science: developing and piloting the quality implementation tool. *Am J Community Psychol.* (2012) 50:481–96. doi: 10.1007/s10464-012-9521-y
60. *InfoSM*. (2020) Available online at: https://www.infosm.blv.admin.ch/evaluation/frequency?lang=en&from=2017-10-09&to=2020-10-09 (accessed Jul 14, 2020).

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.

frontiers in Veterinary Science

BRIEF RESEARCH REPORT
published: 08 June 2021
doi: 10.3389/fvets.2021.647439

How to Strengthen Wildlife Surveillance to Support Freedom From Disease: Example of ASF Surveillance in France, at the Border With an Infected Area

Stéphanie Desvaux[1], Christophe Urbaniak[2], Thibaut Petit[3], Pauline Chaigneau[4], Guillaume Gerbier[5], Anouk Decors[6], Edouard Reveillaud[7], Jean-Yves Chollet[8], Geoffrey Petit[2], Eva Faure[4] and Sophie Rossi[9]*

[1] French Agency for Biodiversity (OFB), Wildlife Health Unit, Birieux, France, [2] Regional Hunters' Federation (FRC), Châlons-en-Champagne, France, [3] French Agency for Biodiversity (OFB), Regional Delegation, Rozerieulles, France, [4] National Hunters' Federation (FNC), Issy-les-Moulineaux, France, [5] French General Directorate for Food (DGAL), Animal Health Unit, Strasbourg, France, [6] French Agency for Biodiversity (OFB), Wildlife Health Unit, Orléans, France, [7] French General Directorate for Food (DGAL), Animal Health Unit, Bordeaux, France, [8] French Agency for Biodiversity (OFB), Wildlife Health Unit, Auffargis, France, [9] French Agency for Biodiversity (OFB), Wildlife Health Unit, Gap, France

OPEN ACCESS

Edited by:
Carola Sauter-Louis,
Friedrich-Loeffler-Institute, Germany

Reviewed by:
Fernanda Dorea,
National Veterinary Institute, Sweden
Anette Ella Boklund,
University of Copenhagen, Denmark

***Correspondence:**
Stéphanie Desvaux
stephanie.desvaux@ofb.gouv.fr

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: 29 December 2020
Accepted: 05 May 2021
Published: 08 June 2021

Citation:
Desvaux S, Urbaniak C, Petit T, Chaigneau P, Gerbier G, Decors A, Reveillaud E, Chollet J-Y, Petit G, Faure E and Rossi S (2021) How to Strengthen Wildlife Surveillance to Support Freedom From Disease: Example of ASF Surveillance in France, at the Border With an Infected Area. Front. Vet. Sci. 8:647439. doi: 10.3389/fvets.2021.647439

Using a risk-based approach, the SAGIR network (dedicated to wildlife disease surveillance) had to strengthen surveillance activities after ASF was confirmed in Belgium in September 2018, very near the French border. Three new active dead wild boars search protocols supplemented opportunistic surveillance in Level III risk areas: patrols by volunteer hunters, professional systematic combing, and dog detection. Those protocols were targeted in terms of location and time and complemented each other. The main objectives of the designed surveillance system were (i) to assure early detection in case of introduction of the disease and (ii) to support the free status of the zone. Compiling the surveillance effort was thus a necessity to assure authorities and producer representatives that the sometimes low number of carcasses detected was not a consequence of no surveillance activities. The human involvement in implementing those activities was significant: more than 1000 8-h days just for the time spent in the field on active search activities. We calculated a specific indicator to enable a comparison of the surveillance results from different zones, including non-infected Belgian zones with strengthened surveillance activities. This was a first step in the evaluation of the efficacy of our surveillance activities in a WB population. Field experiments and modelling dead WB detection probability are planned to supplement this evaluation. Belgium regained its ASF-free status in November 2020, and ASF was not detected in France in either the WB or domestic pig populations.

Keywords: surveillance, wild species, African swine fever, freedom from animal disease, cadaver detection dogs

INTRODUCTION

Since 1986, a network dedicated to wildlife disease surveillance called SAGIR has been in place in France (mainland and overseas territories). SAGIR is a participatory network organising an event-based surveillance, which aims at detecting the principal causes of wildlife mortality (1). The French Hunting and Wildlife Agency (ONCFS) is responsible for the scientific coordination of the SAGIR network [the ONCFS became the French Agency for Biodiversity (OFB) in January 2020].

As African Swine Fever (ASF) spread in Eastern Europe between 2014 and 2018, the level of vigilance was progressively raised within the SAGIR network in France, but no specific area of the territory was assumed to be at higher risk of introduction. The detection of ASF in the wild boar (WB) population in Belgium around 10 km from the French border in September 2018 (2) directly impacted SAGIR's activities. During the first weeks, it was not known how long the disease had been circulating and whether the disease was only concentrated in the Etalle forest where it had been initially detected. French authorities immediately decided to ban hunting in 134 municipalities at the border in order to avoid WB movement and take the time to get a better understanding of the disease distribution (hunting was progressively re-opened from October 20, 2018). Access to forests was also restricted. In this context, the presence of the usual observers of wildlife mortality (e.g., hunters and foresters) was limited, undermining the chance to receive reporting on observed dead WB.

From September 2018, the SAGIR network's objectives in the area bordering Belgium were (i) to assure early detection in case of introduction of ASF and (ii) to support the free status of the zone. To early detect the disease, SAGIR had to detect, sample, and test as many WB carcasses as possible (roadkill included). As the movement restrictions and the hunting ban reduce the chances for passive surveillance, surveillance reinforcement through active carcass search was proposed. Protocols that assured professional and voluntary observation in good biosecurity conditions were developed for three types of searches: (i) hunter patrols, (ii) systematic combing of forest in at-risk forests, and (iii) dog detection. From mid-February 2019, an active surveillance program was also conducted. Twenty percent of the hunted WBs were sampled and tested by RT-PCR (data not presented). We also developed a procedure for dating carcasses (with the support of forensic police) in case of confirmed infection.

Documenting freedom from disease in a wild population is a methodological challenge. Although hunting bags may be used as a proxy for the WB population, it is impossible to know how many naturally dead WBs are present in a territory during a specific period and, as a consequence, how many of them the surveillance activities should detect. In a crisis context, "no carcass" may be understood as "no surveillance" by authorities or producer representatives. It quickly became necessary to collect and document the surveillance effort, in particular for active searches. Surveillance purely event-based was impossible to measure, as it is based on a high number of field actors performing activities not specifically dedicated to surveillance.

In this article, we describe how ASF surveillance activities were conducted from September 2018 to the end of August 2020 in the wild boar population of the region at the border with Belgium. We analysed the surveillance effort for each of the surveillance modalities in order to learn lessons in terms of human resource management in a context of high risk of introduction in an area. We have also developed an indicator to compare surveillance efficacy between zones (in France and in Belgium). Finally, we discussed how those activities contributed to document freedom of disease in the WB population at the border with Belgium.

MATERIALS AND METHODS

Study Area

In September 2018, the French metropolitan territory was divided into three areas using a risk-based surveillance approach (3):

- Level III: infected area or area where infection is suspected (ZBN, ZBC, and ZBS in **Figure 1**),
- Level II B: increased risk of introduction due to proximity (i.e., neighbouring an infected area or an area where infection is suspected) (ZO in **Figure 1**, as well as Corsica Island for its proximity to Sardinia),
- Level II A: increased risk of introduction by long- or medium-distance transmission (the rest of the territory).

No part of metropolitan France was kept in Level I, as this level is the base level in a context of low risk of introduction. Surveillance efforts were thus distributed differently in these three areas. Active search activities were only implemented in the Level III area, including 134 (from 15/09/2018 to 19/10/2018), then 50 municipalities at the border with Belgium (**Figure 1** shows the regulated zones in France and Belgium as defined in April 2019). In January 2019, a depopulation zone (with intense WB destruction activities) was defined within the Level III area. Fences were built progressively to separate this depopulation zone, which in the end overlapped the Level III area. The surface area of the Level III area, as defined in **Figure 1**, was about 300 km^2, divided into three fenced zones (ZBN, ZBC, and ZBS).

Description of the Three Active Carcass Search Protocols

The three protocols for active carcass searches were designed to complement each other in terms of location and time and to supplement opportunist surveillance. Contrary to opportunistic surveillance, they allow to target areas at higher risk of introduction.

Hunter patrols were organised rapidly in September 2018. These were initially planned for a few weeks to help assess the epidemiological situation at the border with Belgium. This activity targeted municipalities at the border with the infected Belgian area ($n = 27$). The objective was to have at least one hunter patrol per week in each hunting ground. Hunters had to organise a search (prospecting), targeting areas with known WB presence based on their experience of the past few years and their field observations. The route should include, if present:

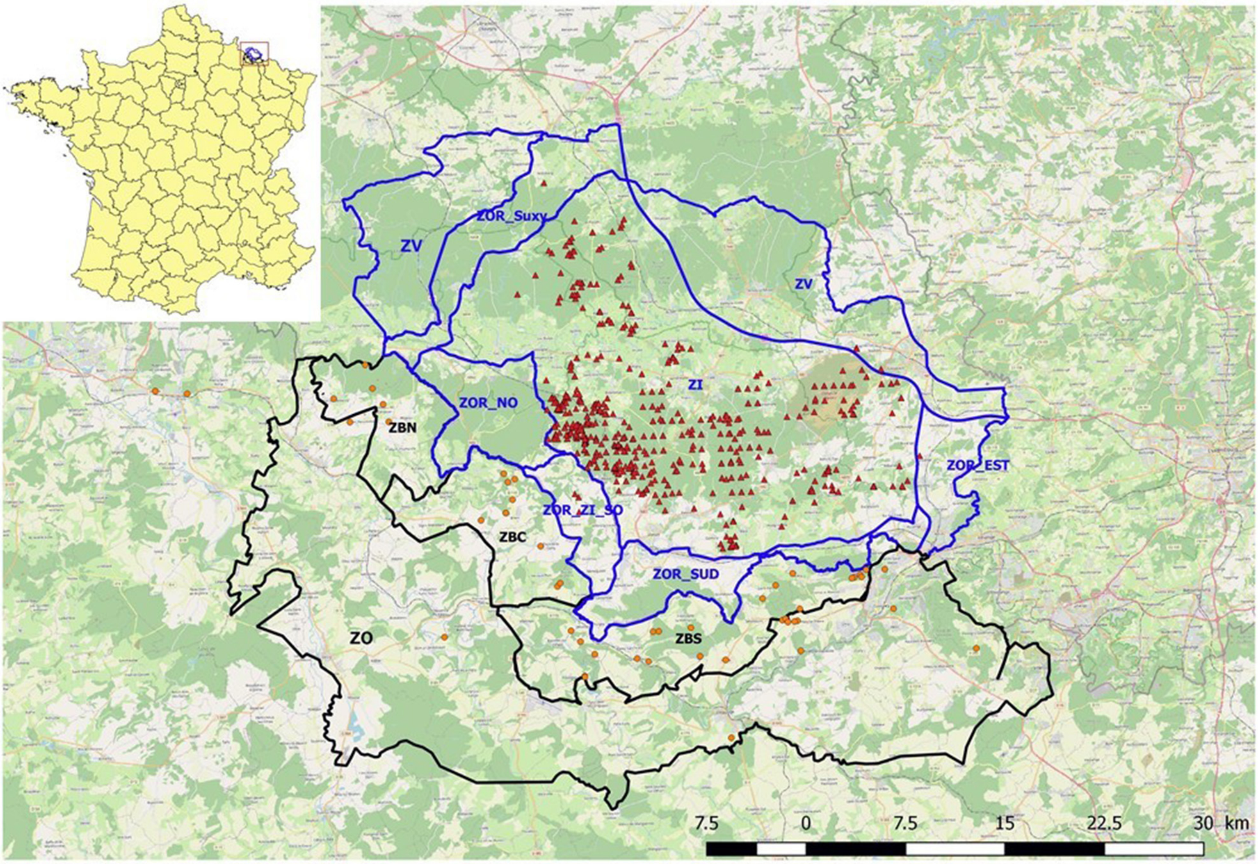


FIGURE 1 | Regulated zones in France (black line, with ZO = Level II, ZBN, ZNC, and ZBS = Level III) and in Belgium (blue line) as defined in April 2019 with all the carcasses collected in the French Level III areas (orange dots) and in the infected Belgian area (red triangle—source OIE) during the study period (September 2018 to August 2020).

- mud and water holes (known to be commonly used by WBs) and feeding grounds as areas known to be attractive to WBs;
- fences and valley where WBs may look for small rivers. Indeed, we know that infected WBs will look for water (because of the fever) and may be more easily stopped by physical barriers and be unable to escape. As a consequence, they may be found dead along fences (4–6).

We rapidly decided to offer the volunteer hunters financial compensation (30 euros per field session).

Systematic combing of forests, unlike hunter patrols, aimed to cover the entirety of a forest area using a method also implemented in Belgium: silent drive "hunt" by teams of around 10 persons. ONF (National Forest Agency) foresters were responsible for supervising the teams made up of military volunteers and ONCFS staff. We selected areas to be combed from forests in buffer zones of 5–7 km from the nearest Belgian ASF cases. Forests shared between France and Belgium were prioritised. This surveillance activity started in January 2019 and stopped in July 2019, when no new cases had been reported <7 km from the border. Between January and July 2019, they were planned every week or every 2 weeks based on a rapid risk assessment analysing the locations of the Belgian ASF cases, the forest continuity between the cases and the French border, and the presence of fences. Planning was also determined by the availability of human resources.

Dog detection was planned for the same at-risk area as the systematic combing but in different locations: at the border of the forests, close to rivers, in pastures and in areas that are difficult for humans to access. In January 2019, three dog handlers contracted by ONCFS started to train their dogs to detect the scent of dead WB, and fieldwork started 3–4 weeks later. During the study period, five other dogs were trained and used in the field. The protocol included restrictions during very hot or very cold periods. A specific biosecurity procedure was developed for this activity, including washing and disinfecting the dogs' legs after each field session (a field day was made up of several field sessions as dogs cannot search for a long time).

For each of those surveillance activities, a specific form was designed, filled out, and compiled. Hunting organisations developed a shared database and were responsible for compiling and entering data for hunter patrols. They also collected forms from foresters and entered data for systematic combing.

The ONCFS compiled the dog detection and systematic combing data.

Weekly National Reports

In addition to weekly summary reports of the number of carcasses detected in each area, we had to report the surveillance effort related to the active search activities performed in the Level III area. The spatial unit used to compile data was the hunting ground. Other authorised activities involving professionals in the field were also reported (forestry work or drive hunts during the hunting season). Although those activities were not specifically dedicated to surveillance, they were performed by people who had received information or training on ASF and knew that it was compulsory to report any dead WBs observed.

Measuring the Surveillance Effort

To better understand the human resources needed for each activity, the surveillance effort was measured by calculating the total number of field sessions, their duration, and the total human involvement in hours (duration of each field session multiplied by the number of people involved). Surveillance effort for opportunistic surveillance was impossible to measure. We also calculated the average spatial coverage—as a line or a surface covered—for each active search activity.

Evaluation of Surveillance Efficacy

To evaluate surveillance efficacy, we developed an indicator enabling us to roughly compare the surveillance results between zones by dividing the number of carcasses detected by a proxy for the WB population. The proxy used is the forest surface area because it is assumed to be proportional to the WB population (7, 8). The forest surface area was extracted from the CORINE Land Cover ® database (2018, vector data). Three classes of vegetation were considered: broad-leaved forest, coniferous forest, and mixed forest.

The zones to be compared included the three zones of our Level III area in France (ZBN, ZNC, and ZBS) and three zones in Belgium at the border with France (ZOR_NO, ZOR_ZI_SO, and ZOR_SUD) (**Figure 1**). Due to their location, the three zones in Belgium present landscape continuity with the French Level III area. Two of them (ZOR_NO and ZOR_SUD) share a similar epidemiological situation with the French zones: they were not infected but close to an infected area. They also experienced active search activities not described in this study. The zone named ZOR_ZI_SO, initially of similar status to the other two, became infected in January 2019 and regained its previous status in May 2020 (9). Data from Belgium surveillance was compiled from the reports produced and shared by the Public Service of Wallonia.

ASF Detection

ASF RT-PCR analyses were performed by local screening laboratories. Two commercial kits were used: ADIAVET ASFV Fast Time and ID Gene ASF Duplex. In case of positivity, the sample would have been sent to the French national reference laboratory (ANSES).

RESULTS

Active Search Activities and Reporting

Hunter patrols were initially planned for a few weeks to evaluate the epidemiological situation in the hunting grounds closest to the Belgian ASF cases. In the end, they were continued until the end of 2020 to support the free status of the zone as well as to guarantee early detection in case of introduction. In total, between September 2018 and August 2020, 2144 field sessions were organised with some fluctuation over the months (**Table 1**).

Systematic combing activities started just after an ASF case was confirmed in two WBs hunted outside the infected and fenced area in Belgium in January 2019 (located in ZOR_ZI_SO in **Figure 1**). Those cases increased the perceived risk of ASF introduction to France. It became even more necessary to assure no unusual mortality affected the French WB population. Rapidly, we experienced difficulties in properly exploring some landscapes, as moving forward in a line can be extremely difficult when brambles are present and during spring and summer. Furthermore, we faced some difficulty in terms of manpower. Thus, in spring 2019, we decided to target areas with higher chance of carcass detection using a model developed by the Belgian team (4). The model was applied to our Level III area, and the total surface area to comb in a forest was thus reduced by around 75%. In total, between September 2018 and August 2020, 57 systematic combing field sessions were organised.

Dog detection was initially planned to supplement systematic combing by targeting areas not easily covered by that activity. We rapidly refined our strategy in order to avoid the dogs having to search for hours in too uncomfortable environment, especially in dead nettles in springtime or in brambles. Dog detection was used from February 2019 to August 2020. In total, between September 2018 and August 2020, 66 field days (with several search sessions per day) were organised. We also had to adapt our biosecurity protocol to properly clean and disinfect the dogs' legs with appropriate products only at the end of the day and not after each search session, as this procedure was a source of stress for some of the dogs.

Reporting was organised on a weekly basis by producing tables with all the carcasses detected and tested for ASF by zone and maps compiling all the search activities at each hunting ground level. Reports were posted on the National Animal Health Surveillance Platform (NAHSP) website (www.plateforme-esa.fr).

Estimation of the Surveillance Effort

Human Resources

The total human involvement for each active search activity (duration of the field sessions multiplied by the number of people involved) is given in **Table 1**. Its shows that hunter patrols mobilised much higher human resources than the other two activities, with a total of 6,128 h dedicated to these patrols, vs. 2,384 h and 384 h, respectively, for systematic combing and dog detection. Although hunter patrols were planned weekly, we observed some fluctuations over the months (**Table 1**). The other activities were planned according to the epidemiological situation.

TABLE 1 | Surveillance effort and carcass detection compiled by active search activity over the study period in France, at the border of an infected area.

		Sept–Dec 18	Jan–Apr 19	May–Aug 19	Sept–Dec 19	Jan–Apr 20	May–Aug 20	TOTAL
Number of field sessions	Hunter patrols	314	352	473	487	264	254	**2,144**
	Systematic combing	0	28	29	0	0	0	**57**
	Dog detection (in days)	0	14	26	11	10	5	**66**
Total duration of the field sessions (hours)	Hunter patrols	643	734	1,071	1,049	607	630	**4,734**
	Systematic combing	0	96	124	0	0	0	**220**
	Dog detection	0	42	59	26	26	9	**162**
Total human involvement (hours)	Hunter patrols	981	992	1,342	1,354	818	643	**6,130**
	Systematic combing	0	1,026	1,358	0	0	0	**2,384**
	Dog detection	0	100	145	59	58	21	**383**
Number of carcasses detected	Hunter patrols	1	0	0	1	0	0	**2**
	Systematic combing	0	4	0	0	0	0	**4**
	Dog detection	0	2	0	0	0	0	**2**
	SAGIR opportunistic surveillance (roadkill)	22 (17)	15 (8)	3 (2)	4	2	0	**46**

The way the field teams were organised was also very different for the three activities. In more than 80% of cases, the hunter patrols were implemented by only one hunter (median: 1, min: 1, max: 17), whereas systematic combing was performed by a team of 11 people on average (median: 10, min: 6, max: 39). Dog detection teams were usually made up of the dog handler(s) and one person from the ONCFS (median: 2, min: 2, max: 4). The duration (in hours) of the field sessions also differed: whereas hunter patrols lasted on average 02:12 per session (median: 02:00, min: 00:15, max: 09:45) over a long period (2,144 field sessions), the field sessions for systematic combing were more limited in number ($n = 57$), but each session lasted on average 03:50 (median 04:00, min: 01:09, max: 06:50). The dog detection teams worked on 66 days from February 2019 to August 2020, with search activities lasting on average 02:30 per day (median: 02:30, min: 00:29, max: 05:40). A working day with the detection dogs was divided into small search sessions of 00:50 on average (median: 00:43) separated by resting and/or training time.

Spatial Coverage

Distance travelled by hunter patrols was 5.6 km on average per field session (median: 4.6 km). Systematic combing covered on average 388 ha per field session (median: 400 ha) with an average speed of 109 ha per hour (median: 104 ha). The distance travelled by dog handlers was 4.7 km on average per field day (median: 4.9 km). We calculated that the dogs covered 2.3 times more distance than the dog handlers.

Evaluation of Surveillance Efficacy

Carcass Detection

In total, 54 carcasses were reported in the Level III zone, 53 were collected and tested using RT-PCR testing, and 1 was not found by the field team (detected on the roadside by an observer) (see **Figure 1** for location). Among those 54 carcasses, 43 were located in the 300-km^2 Level III area as defined in **Figure 1**. Eighty-seven percent of the carcasses were detected during the first year (September 2018 to August 2019) no matter how they were detected (opportunistic or active searches). We observed a similar tendency in the neighbouring Belgian zones sharing similar epidemiological context (ZOR_NO and ZOR_SUD), with 83% of the total number of carcasses being detected during the first year (data not shown).

Opportunistic surveillance (SAGIR) detected 85% of the carcasses in the Level III area (46/54), with most reports made by hunters (37%), farmers or common citizens (22%), and ONCFS officers (15%). If you exclude roadkill (50% of the total number of carcasses detected), the opportunistic surveillance share decreases to 65% during the first year, increasing the share found due to active search activities.

Comparison Between Zones

Table 2 shows the numbers of carcasses detected per square kilometre of forest area for each zone. We observe some differences between the three French zones, with a similar number of carcasses detected per km^2 of forest in the French ZBC and ZBS zones but a lower number detected in ZBN. Compared to Belgian areas, the number of carcasses detected per kilometre square of forest in ZBC and ZBS is similar to the Belgian ZOR_SUD but lower than in ZOR_NO. The ZOR_ZI_SO zone had the highest number of carcasses per kilometre square of forest area, but this zone had a different status to the others as it was declared infected between January 2019 and May 2020.

DISCUSSION

Field Implementation

As presented in the results, we had to adapt the systematic combing protocol because it was arduous to implement and because it was very demanding in terms of human resources. We decided to target forest areas where dead WBs were most likely to be found using the model developed by (4). In a non-infected area at risk of introduction, the priority is to detect a case early. Thus, it is acceptable to target field search activities using a risk-based approach. Conversely, systematic combing is

TABLE 2 | Surveillance efficacy indicators for different surveillance zones in bordering areas of France and Belgium (refer to **Figure 1** for location of the zones).

Country	Zone	Forest surface (ha)	No. of carcasses detected per 100 ha of forest area	No. of carcasses detected per 100 ha of forest area (excluding roadkill)
Belgium	ZOR_NO	4,543	0.88	0.73
	ZOR_SUD	2,469	0.73	0.45
	ZOR_total	**7,012**	**0.83**	**0.63**
	ZOR_ZI_SO	**812**	**2.96**	**2.71**
France	ZBN	2,801	0.25	0.14
	ZBC	2,021	0.54	0.40
	ZBS	4,859	0.49	0.27
	Total Level III area	**9,681**	**0.46**	**0.26**

key to the ASF control strategy in an infected area as carcasses have to be detected and removed from the environment to stop transmission between animals (6).

The results also show that the number of hunter patrols was not steady over the months despite being planned on a weekly basis. Different hypotheses can be put forward. Firstly, although this activity was compensated, hunters were involved on a voluntary basis, so they had no obligation to do the patrols and had to cope with their professional and personal constraints. Secondly, we also perceived it was difficult to keep them motivated across the entire period. Proposed explanations based on feedback we received are that:

- providing appropriate feedback to field actors is a key issue and is never perfect in a crisis context.
- a changing agenda makes it difficult to prepare well. For instance, in the changing and uncertain epidemiological context, we were not able to draw up a long-term plan for surveillance activities from the beginning: hunter patrols initially planned for a few weeks had to be maintained for 2 years.
- policy decisions related to the hunting ban or financial compensation for hunting societies negatively affected communication with hunters and sometimes the data reports.
- delay in paying the patrols similarly complicated communication. Administrative procedures for such payments need to be better anticipated in the future.
- it was also difficult for volunteers to understand the need to report their field sessions on a weekly basis when hunting was re-opened.
- as the expected results in most cases were "no carcass found", those implementing the searches might have experienced a feeling of failure. Our communication probably has to promote the objective of the fieldwork better.

Reporting

Compiling data from different sources and using different spatial scales was not straightforward. It was thus decided to develop a shared database and an Android application supporting spatial data. A prototype was developed and tested using the KoBoToolbox platform (https://www.kobotoolbox.org/). Because it came too late in the programme, this tool was not routinely used in the end.

Surveillance Efforts

By compiling surveillance efforts for all activities, we have a better picture of the true human resource involvement during this crisis. Nevertheless, this evaluation does not take into account the time spent on local or national coordination, nor the time spent on managing the carcasses (sampling and packaging in good biosecurity conditions). Those activities are, however, tricky points in the organisation of the surveillance activities. To complete this picture, a qualitative assessment of the perception of field actors would be necessary: as some activities were very demanding, we perceived that field teams were exhausted after a 1-year period.

Surveillance Efficacy

Fifty-four carcasses were detected between September 2018 and the end of August 2020 in our Level III area, mainly due to opportunistic surveillance. Nevertheless, 50% of them were roadkill known to be less likely to be infected than other carcasses found in ASF-infected countries (10). Thus, they were recorded separately to give a more precise picture of the surveillance results. Without precise knowledge of the WB population, the question of our surveillance system's efficacy in detecting most of the carcasses is difficult to answer. Analysing data from the WB depopulation programme may help to do so. The hunting bag for the 2018–2019 season was 936 animals in the Level III area. In January 2019, fences were built, and a depopulation programme started. Thus, the WB population within the Level III area was under strict surveillance with limited opportunity to move outside the area. Over the 2019–2020 hunting season, the number of hunted WBs within the depopulation programme (by hunters and professionals) was 951 on April 19, 2020 (OFB data). On that date, the remaining population within this Level III area was estimated to be between 150 and 220 animals (based on field observations and data from camera traps—OFB data). Although it is probably imperfect, compiling this data gives a rough idea of the population level within this restricted zone of 300 km^2. Guberti et al. (6) estimate that a desirable goal for dead WB surveillance is to report 10% of the carcasses. They estimated that natural mortality in WBs is 10% of the population.

In our case, if we roughly estimate that 2,500 WBs lived in this area over the study period, around 250 animals may have died naturally. Our surveillance system succeeded in detecting 17% of this estimated dead WB population. In the context of a depopulation programme, the natural mortality percentage is probably even lower due to the intense hunting pressure, and as the depopulation progressed, it became more difficult to found one carcass.

Another way to evaluate our surveillance activities was to compare the French and Belgian surveillance data in similar areas (Belgian ZOR neighbouring the French border). We can hypothesise that the WB population was shared to some extent between the two countries (especially when a forest lays on both sides of the border). Thus, we used a proxy for this population (surface area of the forest) to calculate an indicator of the surveillance efficacy and we observed increased detection of carcasses in proximity to the ASF cases. Thus, proportionally to the forest surface area, more dead WBs were detected in France in ZBC and ZBS compared to ZBN, the farthest zone from the epizootic front. The difference is not only explained by more intense active search activities in ZBC and ZBS. Indeed, the opportunistic surveillance also detected fewer carcasses in ZBN proportionally to the forest surface area. We can hypothesise that the landscape may have influenced observation and thus reporting of carcasses in ZBN (more dense forest area with restricted public access). Nevertheless, field actors' lower awareness cannot be excluded.

Similarly, more dead WBs were detected in the Belgian zones closest to the epizootic front. Proportionally to the forest surface area, more dead WBs were detected in the Belgian ZOR_NO zone compared to ZOR_SUD, not directly in continuity with the infected forest. Similarly, ZOR_ZI_SO, which was classified as an infected area from January 2019 to May 2020, had the highest number of carcasses detected despite only a few (8) confirmed infected cases.

Finally, we note that active search activities interestingly supplement the results of opportunistic surveillance. For instance, between January and April 2019, 50% of the carcasses (excluding roadkill) were detected by active surveillance. Although, in the end, hunter patrols did not detect many carcasses compared to the time they spent in the field, they were a guarantee that no abnormal mass mortality occurred.

CONCLUSION

France remained free from disease, and Belgium regained its free status in November 2020 (11). Despite the proximity between the Belgian infected area and the French border, no regulated zones as defined by the Commission Implementing Decision 2014/709/EU were decided for the French territory. Regular and detailed reporting of surveillance activities on the WB population, together with the depopulation programme in the Level III area, contributed to supporting this free status.

Surveillance of an epizootic in wildlife is always challenging. In this experience, we had to increase the field presence to actively detect new carcasses in a changing epidemiological situation. Those efforts contributed to increasing the number of carcasses detected. They were also a guarantee that no abnormal mass mortality occurred in the WB population.

The study of the surveillance effort and the comparison of the number of carcasses detected by surface area of forest is a first step in the evaluation of the surveillance activities undertaken during this crisis. In order to improve this evaluation, we are planning to organise a field experiment to compare, within an experimental plan, the efficacy of our different active search methods in controlled conditions. The criteria to be controlled relate to visibility and accessibility for the observers (the landscape is being modelled according to those criteria). We also plan to deepen our analysis on the carcass distribution and to better explore the probability of detection by comparing different surveillance efforts in the Level III area in France and the equivalent area in Belgium.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because their are a share property of OFB, FNC and Ministry of Agriculture. Requests to access the datasets should be directed to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because All animals tested were animal found dead.

AUTHOR CONTRIBUTIONS

SD, PC, EF, AD, and SR: active search protocol design. SD, CU, PC, and GP: data compiling. SD: data analysis. SD, GG, PC, EF, and TP: paper writing. SD, CU, TP, PC, GG, AD, ER, J-YC, GP, EF, and SR: critical revision of the manuscript. All authors contributed to the article and approved the submitted version.

ACKNOWLEDGMENTS

We would like to acknowledge the work done by all the field actors: hunters, departmental hunters' federations, OFB and ONF officers, and dog handlers. We would like to thank our colleagues from the Belgian Department of Nature and Forest for sharing their experience and data throughout the crisis period. We would also like to thank the Departmental Veterinary Laboratory of Strasbourg in charge of the ASF testing for the study area, as well as the other members of the national working group on ASF surveillance (Plateforme ESA), who contributed to the definition of the risk-level approach for ASF in wildlife: Florence Baurier and Dominique Gautier (ADILVA), Marie-Frédérique Le Potier and Céline Richomme (ANSES), Yves Lambert and Sebastien Wendling (DGAL), Benoit Bourbon (MTES), and Patrick Bourguignon (SNGTV). Finally, we would like to thank Agathe Le Goff, Emmanuelle Pernot, and Nicolas Toulet (OFB) for their contribution to data compiling as well as Ferran Jori and David Chavernac from CIRAD for their collaboration in developing the KoBoToolbox database (Projet Smart aPPA funded by INRAE).

REFERENCES

1. Decors A, Hars J, Faure E, Quintaine T, Chollet JY, Rossi S. Le réseau SAGIR: un outil de vigilance vis-à-vis des agents pathogènes exotiques. Bulletin épidémiologique Santé animale – Alimentation. *Spéc Vigil Vis-À-Vis Des Malad Exo.* (2015) 66:35–9.
2. Linden A, Licoppe A, Volpe R, Paternostre J, Lesenfants C, Cassart D, et al. Summer 2018: African swine fever virus hits north-western Europe. *Transbound Emerg Dis.* (2019) 66:54-55. doi: 10.1111/tbed.13047
3. Stärk K, Regula G, Hernandez J, Knopf L, Fuchs K, Morris RS, et al. Concept for risk-based surveillance in the field of veterinary medicine and veterinary public health: review of current approaches. *BMC Health Serv Res.* (2006) 6:20. doi: 10.1186/1472-6963-6-20
4. Morelle K, Jezek M, Licoppe A, Podgorski T. Deathbed choice by ASF-infected wild boar can help find carcasses. *Transbound Emerg Dis.* (2019) 66:1821–6. doi: 10.1111/tbed.13267
5. Wozniakowski G, Fraczyk M, Niemczuk K, Pejsak Z. Selected aspects related to epidemiology, pathogenesis, immunity, and control of African swine fever. *J Vet Res.* (2016) 60:119–25. doi: 10.1515/jvetres-2016-0017
6. Guberti V, Khomenko S, Masiulis M, Kerba S. African swine fever in wild boar ecology and biosecurity. *FAO Animal production and health manual no. 22. Rome, FAO, OIE and EC.* (2019). Available online at: https://www.oie.int/fileadmin/Home/eng/Animal_Health_in_the_World/docs/pdf/ASF/EN_Manual_ASFinwildboar_2019_Web.pdf (accessed February 01, 2021).
7. Bosch J, Iglesias I, Muñoz MJ, De La Torre A. A cartographic tool for managing African Swine Fever in Eurasia: mapping wild boar distribution based on the quality of available habitats. *Transbound Emerg Dis.* (2017) 64:1720–33. doi: 10.1111/tbed.12559
8. Bosch J, De La Torre A, Alexandrov T, Iglesias I, Miteva A, Muñoz MJ. Can habitat suitability predict the presence of wild boar? *Suitab Land Uses Vs Georef Data Bulgaria Folia Zool.* (2014) 63:194–205. doi: 10.25225/fozo.v63.i3.a7.2014
9. Official Journal of the European Union. *Commission Implementing Decision (EU) 2020/662 of 15 May 2020 amending the Annex to Implementing Decision 2014/709/EU concerning animal health control measures relating to African swine fever in certain Member States. L 155/27.* (2020). Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020D0662&from=EN (accessed February 01, 2021).
10. Shulz K, Conraths FJ, Staubach C, Viltrop A, Olševskis E, Nurmoja I, et al. To sample or not to sample? Detection of African swine fever in wild boar killed in road traffic accidents. *Transbound Emerg Dis.* (2020) 67:1816–9. doi: 10.1111/tbed.13560
11. Official Journal of the European Union. *Commission Implementing Decision (EU) 2020/1741 of 20 November 2020 amending the Annex to Implementing Decision 2014/709/EU concerning animal health control measures relating to African swine fever in certain Member States. L 392/32.* (2020). Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32020D1741&from=EN (accessed February 01, 2021).

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.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 08 June 2021
doi: 10.3389/fvets.2021.658454

Cross-Sectoral Zoonotic Disease Surveillance in Western Kenya: Identifying Drivers and Barriers Within a Resource Constrained Setting

Lian Francesca Thomas [1,2*], *Jonathan Rushton* [1,3], *Salome A. Bukachi* [4], *Laura C. Falzon* [1,2], *Olivia Howland* [1,2] *and Eric M. Fèvre* [1,2,3*]

[1] *Institute of Infection, Veterinary and Ecological Sciences, University of Liverpool, Leahurst Campus, Neston, United Kingdom,* [2] *International Livestock Research Institute, Nairobi, Kenya,* [3] *Centre of Excellence for Sustainable Food Systems, University of Liverpool, Liverpool, United Kingdom,* [4] *Institute of Anthropology, Gender & African Studies, University of Nairobi, Nairobi, Kenya*

OPEN ACCESS

Edited by:
Ferran Jori,
UMR ASTRE—CIRAD, France

Reviewed by:
Anna Sophie Fahrion,
Federal Research Institute for Animal Health, Friedrich Loeffler Institute, Germany
Cécile Aenishaenslin,
Université de Montréal, Canada

***Correspondence:**
Lian Francesca Thomas
lian.thomas@liverpool.ac.uk
Eric M. Fèvre
eric.fevre@liverpool.ac.uk

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: *25 January 2021*
Accepted: *05 May 2021*
Published: *08 June 2021*

Citation:
Thomas LF, Rushton J, Bukachi SA, Falzon LC, Howland O and Fèvre EM (2021) Cross-Sectoral Zoonotic Disease Surveillance in Western Kenya: Identifying Drivers and Barriers Within a Resource Constrained Setting. Front. Vet. Sci. 8:658454. doi: 10.3389/fvets.2021.658454

Background: Collaboration between the human and animal health sectors, including the sharing of disease surveillance data, has the potential to improve public health outcomes through the rapid detection of zoonotic disease events prior to widespread transmission in humans. Kenya has been at the forefront of embracing a collaborative approach in Africa with the inception of the Zoonotic Disease Unit in 2011. Joint outbreak responses have been coordinated at the national level, yet little is currently documented on cross-sectoral collaboration at the sub-national level.

Methods: Key informant interviews were conducted with 28 disease surveillance officers from the human and animal health sectors in three counties in western Kenya. An inductive process of thematic analysis was used to identify themes relating to barriers and drivers for cross-sectoral collaboration.

Results: The study identified four interlinking themes related to drivers and barriers for cross-sectoral collaboration. To drive collaboration at the sub-national level there needs to be a clear identification of "common objectives," as currently exemplified by the response to suspected rabies and anthrax cases and routine meat hygiene activities. The action of collaboration, be it integrated responses to outbreaks or communication and data sharing, require "operational structures" to facilitate them, including the formalisation of reporting lines, supporting legislation and the physical infrastructure, from lab equipment to mobile phones, to facilitate the activities. These structures in turn require "appropriate resources" to support them, which will be allocated based on the "political will" of those who control the resources.

Conclusions: Ongoing collaborations between human and animal disease surveillance officers at the sub-national level were identified, driven by common objectives such as routine meat hygiene and response to suspected rabies and anthrax cases. In these areas a suitable operational structure is present, including a supportive legislative framework and clearly designated roles for officers within both sectors. There was support from disease surveillance officers to increase their collaboration, communication and data sharing across sectors, yet this is currently hindered by the lack of these formal operational structures and poor allocation of resources to disease surveillance. It was acknowledged that improving this resource allocation will require political will at the sub-national, national and international levels.

Keywords: one health, surveillance, resource allocation, prioritisation, livestock, zoonoses, Kenya

INTRODUCTION

Global awareness of zoonotic disease emergence and the risks these pose both to human health and our global economy has been growing steadily over the last two decades and has been thrown into sharp relief by the ongoing COVID-19 pandemic. Robust, disease surveillance systems are integral to the prevention and control of zoonoses and it has been proposed that many benefits may arise from collaboration between, or even the integration of, surveillance activities across the animal and human health sector. Identifying zoonoses within the animal host prior to transmission to or between humans has the potential to mitigate outbreaks at source, saving lives and potentially large economic burdens (1). The mobilisation of cross-sectoral response teams in the face of an outbreak or in a case investigation allows for operational cost-sharing and can enhance capacity strengthening providing cross-sectoral learning opportunities (2). It is also hypothesised that sharing of facilities, such as laboratories, will enhance the cost-effectiveness of surveillance activities and assist in the retention of laboratory skills by ensuring laboratories work at optimal capacity (3). Routine surveillance activities within humans, animals and food products, with interoperable data sharing between sectors, can assist in the monitoring for presence and trends of pathogen occurrence and identification of risk factors, allowing for appropriate allocation of resources to mitigate the burden of zoonoses and foodborne disease (4, 5).

Such cross-sector collaboration is a key component of the "One Health" (OH) concept, which has been widely championed by the international community and is seen as integral to the success of the Global Health Security Agenda (GHSA) (6–9). Indeed, technical agencies of the United Nations, most notably the World Health Organization (WHO), Food & Agriculture Organization (FAO) and UN Environment Program (UNEP), together with the World Organization for Animal Health (OIE) (the "tripartite plus"), are working together to strengthen OH working at the international level, such as through the Global Early Warning & Response System and through support for the development of national networks (10). Regional bodies, such as Africa CDC and the African Union have also embraced the OH concept to guide their activities and several regional networks have been convened to build capacity and support OH working (11, 12).

Kenya has been proactive in adopting the concepts of OH, with the establishment in 2011 of one of the first dedicated national offices, the Zoonotic Disease Unit (ZDU) (13). The mission of this unit, which sits between the Ministry of Health (MoH) and the Ministry of Agriculture, Livestock & Fisheries (MALF), is to establish and maintain collaboration at the animal, human, ecosystem interface for the prevention and control of zoonotic diseases (14). In line with the GHSA, Kenya has undertaken a prioritisation exercise for zoonoses, has developed a national action plan for Antimicrobial Resistance and a national strategy for elimination of dog-mediated rabies (15–18).

Under the system of devolved governance in Kenya, responsibility for disease surveillance, within the animal and human populations, lies with the 47 semi-autonomous counties as laid out in schedule 4 of The Constitution of Kenya 2010, while the national level retains policy making powers within the health and veterinary sector (19). Counties are under the governance of the County Assembly and the County Executive Committee; with county functions and services subsequently decentralised to the administrative unit of the sub-county under the office of the sub-county administrator as per section 50 of the 2012 County Governments Act (20). The ZDU provides epidemiological support and outbreak response for zoonotic diseases and has provided training for OH focal persons at the county level to encourage cross-sectoral collaboration within the devolved system (16).

Currently there is little documentation on the uptake of cross-sectoral collaboration within disease surveillance at the sub-national level. Understanding what the drivers and barriers are to adopting cross-disciplinary ways of working is an important step in designing strategies to enhance these practises and support potential future integration in surveillance, whilst bolstering the more general aspirations of the scientific community to rollout OH approaches.

We undertook the current study to better understand these drivers and barriers to cross-sectoral collaboration within the current disease surveillance systems at the sub-national level in a country with a stated aim to operationalise OH. The study forms part of the "ZooLinK" programme, which aimed to support the development of an integrated zoonotic disease surveillance system which may serve as a model for other counties in Kenya. We consider surveillance to encompass the systematic collection, analysis, and dissemination of disease data which explicitly contribute to mitigation actions (21). We consider integration to be the institutionalisation and formalisation of a spectrum of collaborative activities between the human and animal health sectors, from regular data sharing or joint disease response activities, to the adoption of a fully interoperable data collection, analysis and dissemination system potentially utilising shared diagnostic laboratories. The different aspects of collaborative processes within disease surveillance have been recently reviewed by Bordier et al. (22).

Whilst a truly OH approach includes integration with data from the environmental sector, for the purposes of this study only the human and animal health sectors were considered. The ZooLinK research programme itself utilised shared diagnostic and data facilities to facilitate dedicated animal and human surveillance teams to collect, analyse and disseminate data on 15 zoonoses of interest within sentinel sites in western Kenya including health care facilities, livestock markets and abattoirs as described in detail by Falzon et al. (23).

METHODS

The objective of the study was to identify themes relating to the barriers and drivers for the integration of animal and human health surveillance systems at the sub-national level. It focused on the 12 sub-counties covered by the "ZooLinK" surveillance activities (23), within the counties of Kakamega, Busia, and Bungoma in western Kenya where several zoonotic infections have been found to be co-endemic (24, 25). The counties of Kakamega, Busia, and Bungoma have populations of 1. 87 million, 0.89 million, and 0.99 million people respectively as of the 2019 population and housing census (26), with mixed crop-livestock smallholdings being the predominant farming system (25).

We conducted semi-structured interviews with surveillance officers across human and animal health sectors in the selected study sites. Semi-structured, key-informant interviews were chosen to allow for narratives to emerge and the ability for the conversation to flow, whilst being guided by questions which aimed to draw out the drivers and barriers to cross-sectoral collaboration. The interview guide can be found in **Supplementary Material 1** but briefly, participants were asked to recall a time in which they were involved with a report of, or response to, a zoonotic disease event and this narrative along with probing questions, was used to tease out aspects of cross-sectoral collaboration and communication. Additional probing questions were included on the flow of information both vertically (from county to national level and back) and horizontally (between counties), the prioritisation process for surveillance activities and strengths and weaknesses of the surveillance systems in general, to gain a greater overview of the workings of the system.

The study used purposive sampling, targeting government officers with direct responsibility for collecting, analysing and disseminating disease surveillance data. **Figure 1** provides a simplified illustration of the current structure of animal and human disease surveillance in Kenya. The specific officers participating in this study and their roles are elaborated in **Table 1**. The initial contacts in each county were the County Director of Veterinary Services (CDVS) and the County Director for Health (CDH), who provided permission to conduct the study and in turn identified the appropriate officers at the county and sub-county level to participate in the interviews, with a total of 30 potential key informants. Our focus was the formal government surveillance system and did not extend to disseminated surveillance by the population, such as participatory disease surveillance systems whereby members of a community actively report disease events (27).

The data collection took place over two periods of 2 weeks each in June and July 2018. Officers were initially contacted by phone to arrange a date and time for an interview and they were visited at their place of work. Those unavailable in the first data collection period were asked for a suitable appointment in the second data collection period.

Twenty-seven semi-structured interviews were conducted with a total of 28 veterinary and public health officers at the county and sub-county level who were available during the data collection period (two officers wished to be interviewed together). The participants and their roles within the surveillance system are described in **Table 1**.

Two of the SCVOs requested to be interviewed together, while all other participants were interviewed in a private space within their place of work in one-on-one interviews. Twenty-six participants were male and two were female (both within the human health sector), reflecting the gender disparity within the decentralised civil service of Kenya, particularly at managerial levels due to multiple structural barriers still present within many institutions (28).

After obtaining the written informed consent of the participants, interviews were conducted by the first author using an interview guide (**Supplementary Material 1**). The interviews lasted between 38 and 95 min, were audio-recorded and transcribed verbatim by the first author. The audio recordings were also supplemented by field notes, predominately noting particular sentences which jumped out during the interview and which were then used to direct some of the initial coding.

Thematic analysis, facilitated by the NVivo12® software (QRS International) (29), was conducted predominately inductively, to determine the emergent themes and sub-themes salient to cross-sectoral collaboration at the sub-national level. NVivo12® is a computer-assisted qualitative data analysis software which provides a user-friendly interface in which to code and sort textual data, a process which previously would be undertaken by highlighting or physically cutting out text and sorting it into groups (29).

After transcription, the transcripts were read several times to aid familiarity. After uploading the transcripts into NVivo12®, specific parts of the text relating to cross-sectoral collaboration were categorised under an initial set of codes. Codes are essentially labels which assign a related meaning to sections of text from different sources as illustrated in **Table 2** (29). The codes were then grouped into an initial set of themes, the content of which were then further interrogated and re-grouped. This process was re-iterated several times, until what we believe to be an inclusive yet parsimonious set of themes were described and no further themes were emerging from the text.

Ethical Approval

Approval was granted by the Institutional Research Ethics Committee (IREC Reference No. 2017-08) at the International Livestock Research Institute, a review body approved by the

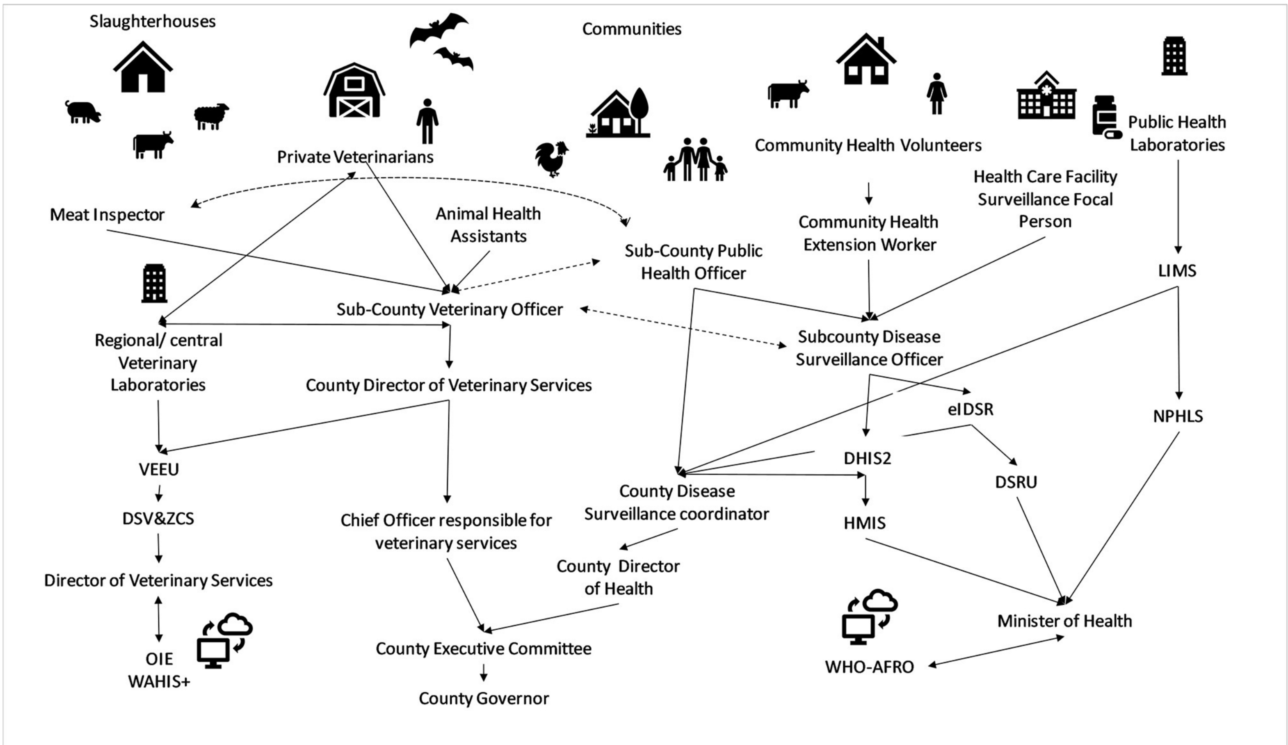


FIGURE 1 | Simplified overview of animal and human disease surveillance information flow in Kenya. ⟶ indicates flow of surveillance data through designated data collection tools. ⟷ indicates data flow in both directions. - - - → indicates lines of communication mandated by disease specific acts (i.e., Rabies Control Act, Meat Control Act) without specific reporting tools. DHIS2, District Health Information System 2, eIDSR, electronic Integrated Disease Surveillance & Response system, HMIS, Health Management information Service, DSRU, Disease Surveillance & Response Unit, LIMS, Laboratory Information Management System, NPHLS, National Public Health Laboratory Services, WHO-AFRO, World Health Organization Africa Region, VEEU, Veterinary Epidemiology & Economics Unit, DSV&ZCS, Disease Surveillance, Vectors & Zoological Control Services, OIE WAHIS+, World Animal Health Information System.

Kenyan National Commission for Science, Technology and Innovation. Approval to conduct the work was also obtained from the Ministry of Agriculture & Irrigation—Directorate of Veterinary Services and the Ministry of Health, and the relevant offices of these Ministries at devolved government level.

FINDINGS

Through the process of thematic analysis, we have identified four themes relating to the drivers or the barriers of cross-sectoral collaboration. We have classified these themes as; "Common Objectives," "Operational Structures," "Appropriate Resources," and "Political Will."

Common Objectives as a Driver of Cross-Sectoral Collaboration in Disease Surveillance

Participants were asked to describe situations in which they had communicated, or carried out joint activities, with their counterparts in the opposite ministry. The majority of participants were able to give examples of cross-sectoral communication and collaboration already taking place with others expressing a desire for a more integrated approach.

> "*If I could advise the national government, this department of public health and the department of veterinary services, they should have at least one unit, if they were brought under one unit and came under one department so that at least these people work as a team*" [MoH7]

Participants have different experiences of integration, reflecting, we believe the somewhat *ad hoc* nature of cross-sectoral collaboration at this time. This is illustrated by the differing reflections of two participants where a surveillance officer from the veterinary sector uses an informal approach to keep lines of communication open, and the officer from human health has experienced a reactive system which comes to life when needed.

> "*Interaction* [between sectors]*, more or less on a daily basis, it can be formal or informal [...] but there is a lot of transmission of data*" [MALF2]
> "*This system* [of One Health] *is weak, but it becomes active if we have an outbreak [...] It depends on the situation, when things are calm the links are down but when we have outbreaks we receive communications and share information*" [MoH5]

Details were requested on the focus of interactions which the participants had experienced. These interactions focused on a handful of issues which were consistently highlighted, being

TABLE 1 | Study participants and their roles and responsibilities within disease surveillance in Kenya.

Role	Acronym	Responsibilities	Number participating
County director veterinary services	CDVS	• Responsible for the management of veterinary services across the county including the organisation of surveillance and the planning and co-ordinating of disease control programs. • Receives and aggregates data from SCVOs and reports by email to the head of the Veterinary Epidemiology & Economics Unit (VEEU) who are responsible for analysis of data and onward reporting. • The CDVS also report to the county executive committee via the chief officer	3 (1 acting)
Sub-county veterinary officers	SCVO	• Implement veterinary services at the decentralised unit, including disease control activities and surveillance. • Received written or SMS reports from meat inspectors and animal health assistants collates and report to the CDVS.	12
County disease surveillance coordinators	CDSC	• Responsible for the planning, formulation and supervision of disease surveillance activities in the county. • The CDSC islsis expected to analyse electronic Integrated Disease Surveilannce & Response (eIDSR) and District Health Information System 2 (DHIS2) data on a weekly basis • Reports and reports to the County Director of Health who in turn reports to the County Executive Committee	3
Sub-county public health officers	SCPHO	• Coordinate public health activities at the sub-county level including disease control services, inspect food processing and retail establishments and receive disease reports from community members. • Report, by phone or hard copy to the SCDSO or direct to the CDSC where a SCDSO is not in post	7
Sub-county disease surveillance officers	SCDSO	• Implements disease surveillance activities within the sub-county. • Obtains reports from health facility surveillance focal persons by SMS or hard copy, aggregates and uploads data onto eIDSR and DHIS2. • eIDSR and DHIS2 data can be viewed by the National level units—Health Management Information Systems (HMIS) & Disease Surveillance & Response Unit [(HMIS & (DSRU)].	4

response to dog-bite events or suspected rabies cases, carrying out meat hygiene related duties, and responding to potential anthrax cases.

> *"Yes, actually that's one of the main things we work with public health on [. . .] they* [those bitten by dogs] *end up in our office to find out if the dog was vaccinated or not, we have been working closely with public health on dog bites"* [MoA9]
> *"We also have meat products, we do surveillance of products, our colleagues* [in the DVS] *inspect meat at the slaughterhouse and when it reaches the butchery we come in, we monitor at the butcheries and if we hear from the community that 'so and so was bringing meat in a sack' we follow-up [. . .] so that is how we collaborate with the veterinary department"* [MoH6]

The nature of the cross-sectoral collaborations reported to us by participants were predominately reactive (to dog-bite cases) rather than pro-active (vaccination, dog management and community sensitisation). We have designated these issues as "*common objectives*" and see them as the most proximal driver of cross-sectoral collaboration. The particular examples of common objectives appear to be closely linked to the available "operational structures" we identified from our study, which are discussed in the following section.

Operational Structures as Drivers or Barriers for Cross-Sectoral Collaboration in Disease Surveillance

Under "operational structures" we grouped issues which arose pertaining to the legislation guiding the work of disease surveillance within each sector, the hierarchies and protocols which guide the interaction of the officers, and data sharing platforms or protocols. The presence of these factors is a driver to action on "common objectives," while absence of any one factor becomes a barrier.

Regulatory Environment

The need to have a supportive regulatory environment came out clearly in providing a structure within which officers from the two ministries can work. The response to suspected rabies cases and meat hygiene were seen to be facilitated by the clear demarcation of responsibilities, enshrined in legislation under the Rabies Act (Cap 365), Animal Diseases Act (Cap 364), Meat Control Act (Cap 356), and the Food, Drugs & Chemical Substances Act (Cap 254). These pieces of legislation provide officers from the veterinary services and Ministry of Health, respectively, the authority to act in a co-ordinated manner within differing parts of the system.

TABLE 2 | Code Book describing codes emerging from the transcripts and the themes under which they were grouped.

Overarching theme	Code(s)	Description
1.0_ Common objectives	1.1_Issues for action	Used to capture comments that talk of communication or actions taken with other ministry on specific topics
	1.2_Examples of action	Used to capture comments that describe the type of action taken and frequency thereof
2.0_ Operational structures	2.1_Legislation & targets	Used to capture comments that describe legislation relevant to surveillance activities
	2.2._Hierarchies & protocols	Used to capture comments describing relationships between actors and the protocols or hierarchies which govern those relationships
	2.3_Data sharing	Used to capture comments on the mechanisms by which data could be shared, both within each sector and between sectors
3.0_Appropriate resources	3.1_Resources	Used to capture comments that describe the concerns of actors regarding the presence and absence of resources (financial, infrastructural and human) required to do their job
4.0_Political will	4.1_Political_interests	Used to capture comments regarding national and sub-national interests and priorities and the drivers of these including pressure/interests from voters
	4.2_External interests	Used to capture comments regarding international (Inc. international organisations, donors etc.) interests and pressures

"We have the animal diseases act which gives [officers] *the mandate to carry out any inspections [. . .] The meat control act specifically addresses the issues of what is consumable or not"* [MALF10]

"If we have cases here of dog bites they are assessed by the clinical officer, then we will advise on the anti-rabies vaccination [. . .] at that point we will liaise with the veterinary officer to take action on the dogs" [MoH10]

Formal Lines of Communication

Observation of existing hierarchies and protocols were seen as an important factor in enabling communication of officers between sectors and it was generally felt that enhancing collaboration would require new formal structures for communication and data sharing.

"[. . .] these things need to be structured, I cannot walk in and say the DVS has sent me here to discuss disease [. . .]" [MALF4]

One county has a OH focal person, a veterinary officer, in office, providing a formalised route for cross-sectoral collaboration. Within this county, adhering to formal lines of communication was identified as being a cornerstone for success of the initiative.

"We have been having meetings under the One Health office [. . .] it's not just in passing, it's a formal way of interacting." [MALF11]

While the formation of County OH units is a stated priority, they are yet to be implemented across every county. Where such formal structures are not yet in place there is a reliance on personal relationships between the surveillance officers in different sectors to facilitate informal collaborative networks. Such informal networks do not lend themselves to building institutional memory and may be lost as staff retire or move on.

". . . they [communications] *tend to be more personal,* [depending on] *which officers are holding the office. Once there are good relations, it goes down to the other staff"* [MALF10]

Devolution, whilst allowing innovative solutions to complex health and veterinary problems to be formulated at a local level, was identified by participants as leading to further complexities within disease surveillance providing the potential to slow the transmission of data between sub-national level and across county borders.

"*It's like we* [the counties] *are now different groups, we rarely interact*" [MALF8]

Data Sharing

In addition to formal channels of communication there is a need for effective data sharing between sectors. There is currently no interoperable data sharing platform for human and animal health data sharing at the sub-national or indeed national level. Participants also spoke of difficulties in data sharing within their own sectors which must be addressed to ensure timely, accurate flow of data from the sub-national level to the national. Appropriate feedback to the sub-national level was identified as being of significant importance to the action of disease surveillance. A lack of such feedback, even in the form of negative consequence for non-reporting, was cited across both sectors as a disincentive to reporting, leading to demotivation of officers.

"Disease reporting in the county is almost dead, because you know when you report on this and this situation you also expect feedback and when there is no positive feedback people get wearied out and then stop. Because even when you reprimand they say, last time you did nothing, why should I waste my energy?" [MALF10]
"I think [the data is used] *at county level and national, I'm not sure. . . they* [the national ministry] *just keep information [...] we used to have quarterly data review meetings, but last year they stopped happening"* [MoH11]

Appropriate Resources as a Driver or Barrier for Cross-Sectoral Collaboration in Disease Surveillance

The operational structures which facilitate cross-sectoral collaboration on common objectives require appropriate resources at all levels. Participants in our study identified aspects of financial, human and infrastructure resources as currently hindering their disease surveillance activities and ability to collaborate across sectors.

> *"What blocks me most is lack of personnel to do the work, the second is resources, financial, transport, movement …we don't have a laboratory e.g., so whenever you have a case, you just do it by clinical diagnoses, you can't confirm and say 'this was rabies, this was anthrax'."* [MALF9]
> *" The challenges are financial constraints. We are not able as one health, to attend meetings, we are 2 ministries so bringing people together requires resources"* [MoH3]

To achieve the resource commitments needed requires decision makers in charge of resources to have the will for a change; this is explored in the next section.

Political Will as a Driver or Barrier for Cross-Sectoral Collaboration in Disease Surveillance

Participants identified several different parties who had an influence on the operation of disease surveillance at the sub-national level. These interests were identified as being related to setting priorities and subsequent resource allocation to surveillance activities.

Particularly relevant to zoonotic disease surveillance, we noted a disparity in the prioritisation of zoonotic diseases between the animal and human health sectors. Zoonotic diseases were cited by all participants from animal health as being amongst their priority diseases, with rabies (15 respondents) and anthrax (13 respondents) being most common. Within human health however, only one participant felt that zoonoses (anthrax and brucellosis) were a local priority. Interestingly, this officer was located in a county with an active OH focal person. Participants reported that priorities are set at the county level, but are often aligned with the national targets.

> *"They* [the county priorities] *are the diseases stipulated at the national level for eradication: that is AFP* [Acute Flaccid Paralysis], *measles […] As a county we* [also] *have conditions, maternal death, malaria, that are the diseases of priority"* [MoH11]

Participants were aware that prioritisation at international, national and sub-national level is needed to ensure that appropriate resources are provided to surveillance and disease control activities, with participants perceiving a particular lack of interest in surveillance from budget holders at the sub-national level. The priorities of technical staff were seen to be subsumed by the priorities of the elected members of the county assemblies and the political appointees within the county executive committees (CEC). The CECs have control of the budgetary allocations with participants believing that they prioritise "curative" health care or "visible" investments such as agriculture inputs (fertilisers etc.) over surveillance activities.

> *"The people at the top, they don't consider surveillance as a priority […] they prioritise purchase of inputs, fertilisers, many millions on fertilisers, tractors, to give an impression to farmers that resources are close to them."* [MALF11]

Some participants perceived that momentum may be growing at the national level, but were sceptical that this interest was likely to be translated into resource allocation at the sub-national level.

> *"The top brass were in a seminar in Kisumu and emphasis was put on putting some resources on the prevention and control of zoonotic diseases. How successful that was remains to be seen as all the county governments have their own priorities. You can budget for anything but the county assemblies divert it for some other use"* [MoH3]

Participants were also very aware of the re-enforcing cycle of political will, where lack of funding leads to lack of data leads to lack of political will *Ad infinitum*.

> *"Because no one is funding it, no one is questioning, no one wants to know what happens in surveillance. The county sees health as treating, it doesn't see health as preventing and informing, so it doesn't actually see that there is a need for surveillance. It* [the county] *sees surveillance as an item that is eating the money without giving back. They would rather see that we buy medicine, equip our hospital."* [MoH4]

National and county priorities were seen to be influenced in turn by those of the international community and other external funders. External funders were acknowledged by participants to come with their own specific interests. WHO and the "Global Fund" (to fight AIDs, TB and malaria) were among those external bodies who were identified to drive the health agenda, and the potential for such external support to enhance the surveillance of zoonoses was discussed.

> *"Generally we have a problem when it comes to surveillance, it's not like those diseases, AIDS, TB and malaria funded directly by the Global Fund. But for surveillance, if we get a sponsor to support us we could be able to manage those* [zoonotic] *diseases very well"* [MoH7]

International interest in Avian Influenza (AI) had previously led to the formation and training of rapid response teams. A subsequent scare in neighbouring Uganda galvanised local response, demonstrating the potential for local and international interests to converge and provide appropriate support for OH.

> *"We were trained sometime in 2014 on AI, how to detect, how to respond, how to form a rapid response team. When there was a scare last year in Uganda, we communicated, and we prepared ourselves, we were on the alert, we talked to the public health officer, the nursing officer, the Deputy County Commissioners and even the police… we prepared to handle any eventualities but luckily enough there were no cases"* [MoA5]

The interest in such events, while important in galvanising collaboration, has however, the potential to be transitory, with the potential that technical officers are pulled from one activity to the next as focus of politicians shifted.

"I think maybe what happened is the scare somehow faded, because when there was the first scare, county leadership really wanted to know what was happening. It's [Avian Influenza] *on the news everywhere and we tried to take some steps, but then the information slowly faded so I think they* [politicians] *forgot about it."* [MoA8]

DISCUSSION

In our study we identified four key themes; "common objectives," "operational structures," "appropriate resources," and "political will" which were related to the drivers and barriers for cross-sectoral collaboration by disease surveillance officers at the sub-national level. The most proximal driver for collaborative actions between sectors are "common objectives." Action on these common objectives is facilitated by the presence of "operational structures" such as specific legislation, clear reporting protocols and interoperable data sharing systems. Setting up and working within these structures requires "appropriate resources" including finance, human resource and physical infrastructure such as laboratories, vehicles, IT and consumables. The allocation of such resources is driven by "political will" at the international, national and sub-national level, with this political will and the resource and structures which flow from it in turn influencing the common objectives, the pursuit of which drives action.

These themes sit within a framework which can be visualised as a "hierarchy of needs" with a self-reinforcing feedback loop, as illustrated in **Figure 2**. We see the themes interacting in a sequential way in which each theme becomes a facilitator of the next. In this way the presence of political will allows the allocation of appropriate resources, facilitating the operational structures within which action can be taken on areas in which the objectives of each sector align. A feedback loop then exists where once disease surveillance data are collected, analysed or disseminated in a cross-sectoral manner, the data themselves may reinforce the political will upon which the drivers of collaboration are built. The absence of any one of these identified themes acts as a barrier to the successful implementation of cross-sectoral collaboration within disease surveillance.

We had anticipated that the alignment of disease surveillance priorities in the human and animal health sectors would be a driver for "common objectives," yet the common objectives we identified were not necessarily aligned to the sector priorities as stated. Animal health officers prioritised zoonoses, particularly anthrax and rabies, as per a prioritisation exercise driven by the GHSA (15). Diseases identified as being priorities for surveillance within human health were very closely aligned to those described within the Integrated Disease Surveillance & Response framework standard case definitions for priority diseases in Kenya and were predominately non-zoonotic.

Acute flaccid paralysis as a syndrome indicative of poliomyelitis was mentioned by all human health surveillance officers interviewed as being a surveillance priority reflecting the influence of priorities set by international targets. Poliomyelitis has been earmarked for eradication through the Global Polio Eradication Initiative (GPEI). GPEI is now embarking upon the "endgame" strategy 2019–2023 but until eradication is achieved, there remains a risk to poliovirus free-countries and as such it was declared a Public Health Emergency of International Concern within the International Health Regulations 2014.

Our interpretation of the data is that at the sub-national level the "common objectives" are currently driven primarily through the presence of "operational structures," specifically legislation. Specific pieces of legislation were recognised by participants as providing clearly demarcated responsibilities for officers such as the Animal Diseases Act (Cap 364), Meat Control Act (Cap 356), the Food, Drugs & Chemical Substances Act (Cap 254) and the Rabies Act (Cap 365). These acts provide clearly demarcated roles to actors from both veterinary and public health sectors, implicitly recognising the interconnectedness of human and animal health in relation to zoonoses and food safety, despite not being explicitly built upon OH principles. The presence of this legislation indicates that "common objectives" have, at the point of legislating, been prioritised at one or more of the policy making levels (international, national or sub-national).

We suggest therefore, that legislative frameworks are a powerful driver of collaborative surveillance and the existence of legislation is in itself an indication of the presence of political will at one of the policy making levels (international, national or sub-national). The importance of appropriate legislation, which clearly demarcates roles and responsibilities to allow cross-sectoral collaboration has been highlighted in a recent global review of integrated surveillance systems by Bordier et al. (22).

Participants in this study identified formalised mechanisms of communication and data sharing between the human and animal health sectors at the sub-national level and between the sub-national and national levels as a key requirement for effective service delivery. These issues have previously been highlighted in reports from two evaluations conducted in 2017 by the WHO and the FAO. The joint external evaluation evaluated the IHR capacity of Kenya, whilst the FAO Surveillance Evaluation Tool (SET) evaluated animal disease surveillance including zoonoses (30, 31). Both reports commended Kenya on its leadership in the implementation of cross-sectoral integration through the ZDU, although both evaluations identified specific weaknesses relating to the lack of formalised communication forums and lack of systematic data sharing between sectors, particularly at the sub-national level.

The formal integration of data streams currently collected within distinct, highly vertical structures governed by differing pieces of legislation is a complex challenge to address. Several examples are available of the integration of human and animal health data within a unified system (22, 23, 32, 33) yet it is important that any system implemented fits within existing structures without duplication of effort, has the appropriate legal basis regarding data ownership, confidentiality etc., and appropriate resources to facilitate its implementation.

An aspect of data sharing which was not raised by participants, biased as this study was toward public sector stakeholders, is the additional need for appropriate data sharing between the public and private sectors. The collection of disease surveillance data by private sector actors is of particular interest within the veterinary sector, where private veterinarians are often the front-line service

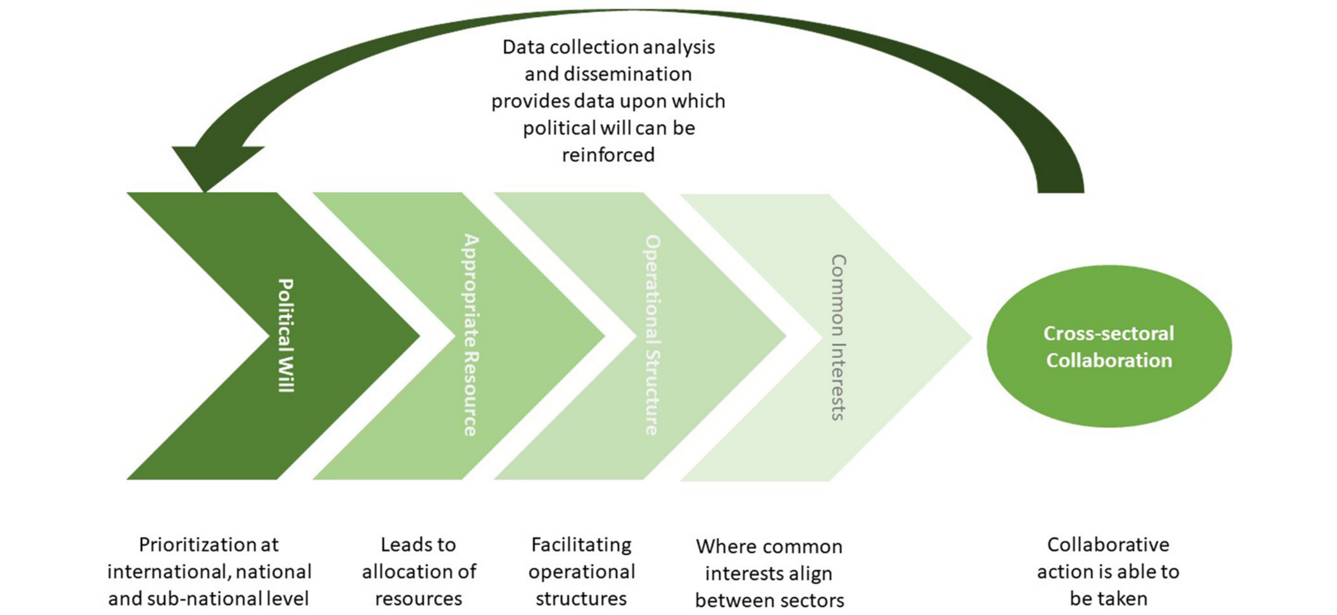


FIGURE 2 | Conceptual framework of how identified themes enable cross-sectoral collaboration within disease surveillance activities.

providers and where agri-food businesses may regularly collect data for their own internal management practises.

Private veterinarians in Kenya are currently mandated to report only notifiable diseases under the Animal Diseases Act (Cap 364). Despite the privatisation of veterinary services across sub-Saharan Africa following the structural adjustment policies of the 1980's, the private veterinary sector in Kenya is still outweighed by the public sector, particularly outside of urban, and highly productive agricultural zones. Approximately 1/3 of all veterinarians in the country are currently within the private sector, but approximately 95% of the data reported into the surveillance system come from public sector actors, indicating a potential ongoing bias in reporting to the detriment of the national surveillance performance (Dr. Kahriri, VEEU, *Per. Comms.*).

Strengthening the participation of the private sector in disease surveillance activities was a key recommendation of the 2011 OIE PVS mission (34). As the commercialisation of agriculture continues across East Africa with the formation of larger, more industrial agri-businesses, these public-private linkages within disease surveillance will become ever more important, including with private veterinary para-professionals whose services often dominate in pastoral areas (35). There are examples where private sector data have been successfully integrated into publicly funded surveillance platforms (36). It is important however, that full consideration is given to the basis on which such data sharing occurs which may require a legislative framework, covering data ownership and data use.

An appropriate financial model which facilitates the integration and use of data collected across animal and human health, as well as recognising the benefits accrued across the public and private sectors, is urgently needed and the allocation of resources to surveillance was a ubiquitous theme raised by participants in this study. As the implementation of disease control and surveillance is now the responsibility of the devolved governments, the process of prioritisation and building of political will at the sub-national level is crucial in order that appropriate allocation of resources is achieved. In accordance with findings in other counties, participants in our study perceived the priorities of county governments to be agricultural inputs (fertilizers, seed) or "curative" health services, both of which may potentially be more visible to the electorate than issues of disease surveillance. Surveillance systems within both sectors are therefore under considerable resource constraints to fulfil their current mandate.

Stimulating investment in surveillance activities in general, and cross-sectoral collaboration specifically, must be done within the context of competing priorities within constrained public expenditure on health and agriculture, both of which currently fall below the internationally agreed targets. The 2003 Maputo Declaration stipulated that countries should allocate 10% of public expenditure on Agriculture, while the 2001 Abuja Declaration set a target of 15% of public expenditure to be allocated to health (37, 38). Between 2013 and 2017, public health expenditure on health in Kenya averaged 6.4% of total government spending, with public agricultural expenditure averaging 5.5% over the same period.

At the sub-national level, counties in Kenya are predominately reliant on an equitable share of nationally raised revenue (84%) in combination with conditional grants (5%) and locally raised revenue (11%). Absorption rates of the county governments from the national allocated budgets have slowly increased but remain low, with an average absorption rate of 65% in 2016/17. Budgetary absorption indicates the ability of the counties to spend the budgetary allocation and is positively associated with efficient and effective budgetary management, which in turn relies upon strong capacity within the county finance departments (39). Local revenue collection also lags behind projections with only 22 counties in 2016/17 achieving an average 60% of their revenue collection targets (40).

It is within this context of resource constraint that new mandates, such as cross-sectoral collaborative structures, must make a business case to the CECs and the county assemblies, who are responsible for budgetary allocation at the sub-national level.

Initial investment in the operational structures required for the implementation of integrated surveillance programmes may be beyond the reach of national and particularly sub-national budgets, and this is an area in which external catalytic funding may play a role (41). The national rabies elimination strategy (NRES) acknowledges that current funding from the ministries is insufficient and that a variety of funding sources, including external donors, is required for implementation.

There is currently an explicit expectation by the ZDU that external support will be required to fully operationalise its' mandate at the sub-national level (16). Reliance on external donors, however, must be undertaken with caution as it has the potential to undermine the national or sub-national strategic priorities. Analysis by the World Bank suggests that approximately 1/3 of health expenditure in Kenya is via donor spending, the majority of which is not aligned to government priorities (42). A review of global public health expenditure by the WHO re-iterated this disconnect, demonstrating that 46% of all donor funding for health is channelled to HIV/AIDS, TB and malaria, but that this funding does not directly correlate with either national prevalence levels of these diseases or the GDP per capita of the countries receiving external funding (43).

In the context of animal and human health systems which already lack sufficient public funding, it is important that any drive to strengthen cross-sectoral collaboration at the sub-national level is done in a way which does not detract from operation of the underlying systems, but rather actively strengthens them (44, 45). It is also important that any systems used for cross-sectoral communication and data sharing do not add to an already confusing surveillance structure, particularly within the animal health sector where numerous surveillance tools are currently being utilised in an un-coordinated manner (30).

At a national and sub-national level, stimulating investment for cross-sectoral activities will require incorporating the concept within the key strategy documents for the "parent" ministries. Currently, neither the Kenya Health Policy 2014–2030, nor the Agriculture Sector and Development Strategy 2010–2020, nor the National Agriculture Investment Plan 2019–2024 explicitly reference such activities in the context of infectious disease (46, 47). Similar omissions are made in the integrated county development plans of Busia, Bungoma and Kakamega counties (48–50).

It would be useful to build upon the data collected through our study with the perspectives of those working in political positions to better understand their resource allocation decisions. Several counties are in the process of bringing county level legislation into law for public health and animal health (Dr. Ogendo CDVS Busia County, *Per. Comms.*). The process of formulating county-level legislation not only clarifies the counties' position in post-devolution Kenya but also provides an opportunity to ensure legislation is fit for purpose where remnants of colonial era legislation still exist. It will be interesting to observe if this enhances the agency of the county governments to improve resource allocation to disease surveillance. Conversely, county-specific legislation may further fragment an already decentralised disease surveillance system and result in slower response to diseases which occur across county boundaries.

Allocation of resources at the sub-national level will also be guided by the evidence of the cost-effectiveness of surveillance and of cross-sectoral collaboration, as exemplified by the statement "*It* [the county] *sees surveillance as an item that is eating the money without giving back.*" More robust surveillance data collection systems and importantly the utilisation of that data is needed to inform economic analyses both for "traditional" and "integrated" surveillance systems. Little empirical data are yet available on the cost-effectiveness of integrated systems. Furthermore, novel cost-sharing structures are required to ensure that costs are correctly attributed across sectors in proportion to where benefits are accrued, as illustrated by the proposals for cost-sharing in relation to brucellosis vaccination in Mongolia (51).

Spending budget lines across differing ministries may be challenging and therefore cost-sharing scenarios may also require novel financing modalities, such as a dedicated shared budget envelope for the surveillance and control of zoonotic diseases. In Kenya, the existence of the ZDU may facilitate such an innovation, yet the concern is that this may result in a dedicated zoonoses surveillance system running in parallel to the "core" business of the 2 ministries, rather than encouraging truly collaborative or integrated working.

A greater understanding of the correct attribution of costs and benefits of OH interventions could conceivably allow for allocations made to one sector (i.e., veterinary services) to be counted against public expenditure targets in another (i.e., human health), if the expenditure can be empirically associated with benefits in the latter sector. This may allow for appropriate resource reallocation while allowing countries to reach their targets for public expenditure, such as those set through the Abuja & Maputo declarations (37, 38).

Conceptual frameworks have been constructed to assess the cost-effectiveness of integrated surveillance which include the need to provide evidence of the intangible benefits of working in a collaborative manner (1). Several intangible benefits of OH working have previously been identified and may include; an increase in social and professional capital for the surveillance officers through expansion of their networks and technical capacities, improved professional opportunities, improved trust between sectors and an increased peace-of-mind for officers who can base their risk assessments and actions upon a greater pool of data (5, 52). The collection, analysis and dissemination of high-quality surveillance data provides a reinforcing loop in the identified themes, being a conduit to building the political will upon which the other themes stand.

The four themes which emerged from this study as being key facilitators of cross-sectoral collaboration within disease surveillance have synergies with some of the organisational criteria identified by Bordier et al. through which "OH" surveillance systems may be evaluated. The need for relevant common objectives, a range of vital operational structures, and the need for appropriate resources, was identified as being fundamental aspects of a functional collaborative system (53). Evaluation frameworks such as that proposed by Bordier et al. (53) and the Network for Evaluation of One Health (NEOH) (54) will be increasingly useful as OH continues to be operationalised in different contexts. The integration of these tools with new initiatives such as the IHR-PVS bridging workshops (55) would be a useful step to support countries wishing to advance both their sector specific and cross-sectoral goals.

The current study wished to understand the perceptions of disease surveillance officers within three counties of western Kenya on the barriers and drivers for cross-sectoral collaboration. The breadth of perspectives was limited and currently exclude those of politically appointed officers and frontline workers, including those in the private sector. It would be useful to elaborate on the current study and triangulating the themes identified here by working with a wider range of stakeholders, potentially across a wider geographical range.

Interviews for this study were conducted individually and therefore could not produce a combined consensus on issues. Focus group discussions or stakeholder workshops may have helped to produce such a consensus, though the information from this study provides a good basis on perspectives which future studies may build on. This study was conducted by a research team who have worked within the arena of "One Health" for many years and we acknowledge our potential bias in viewing cross-sectoral collaboration as a good to be maximised, based also upon the stance of both the national and international community.

Overall, the data analysis indicates constraint to developing and sustaining collaborative effort for integrated surveillance. There are some elements of collaboration which appear to work, but largely the institutional environment (the rules and their enforcement) does not encourage systematic collaborative practices. Due to this weak institutional environment, the allocation of resources to such activities has not been embedded in the system. Additionally, the element of prioritising diseases and health problems at a local level appears to be poorly institutionalised and draws predominately on national or even international priorities. Strengthening local prioritisation of health issues will require a focus on quantification of burden through robust surveillance data, along with the identification of key mitigation activities. In this way it would be easier to better evaluate the ability of integrated surveillance to yield net benefits to public health, and in turn stimulate further investment in such.

CONCLUSION

Our study comprised in-depth interviews with disease surveillance officers from the human and animal health sectors within three counties of western Kenya. These in-depth narratives shed light on the perceptions of the barriers and drivers of cross-sectoral surveillance activities. The themes we identified emerging from these interviews relate to a pathway where collaborative activities occur in response to "common objectives" facilitated by the availability of "operational structures" and "appropriate resources," in turn driven by "political will." The absence of any one of these themes would become a barrier to operationalising cross-sectoral collaboration and we suggest that the pathway becomes self-reinforcing where the collection, analysis and dissemination of surveillance data can in turn strengthen political will.

We suggest that sub-national governments, both in Kenya and beyond, should be engaged to determine what resource allocation can realistically be achieved for disease surveillance, and supported to make allocation decisions based upon robust empirical data on disease burden and economic analysis. The common objectives identified: responding to rabies and anthrax cases and safeguarding meat hygiene, that currently drive cross-sectoral communication and collaboration could be embraced as entry-points to improve the integration of animal and human health surveillance in Kenya. The epidemiological and economic data generated through a strengthened disease surveillance system with appropriate mechanisms for cross-sectoral collaboration, communication and data sharing must then be analysed and disseminated to provide continued stimulus for investment.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institutional Research Ethics Committee (IREC Reference No. 2017-08) at the International Livestock Research Institute. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LT conducted the key informant interviews, transcribed recordings, undertook the thematic analysis, and produced a first draft of the manuscript. SB, LF, and OH supported the analysis and writing. EF and JR obtained funding, contributed to the conceptualisation of the study, and reviewed the manuscript. All authors read and approved the final draft of the manuscript.

FUNDING

This work was supported by the Biotechnology and Biological Sciences Research Council, the Department for International Development, the Medical Research Council, the Natural Environment Research Council and the Defence Science &

Technology Laboratory, under the Zoonoses and Emerging Livestock Systems (ZELS) programme, grant reference BB/L019019/1, and the CGIAR Agriculture for Nutrition and Health (A4NH) programme, led by the International Food Policy Research Institute (IFPRI). We also acknowledge the CGIAR Fund Donors (https://www.cgiar.org/funders/). LT was supported by the University of Liverpool-Wellcome Trust Institutional Strategic Support Fund, the Soulsby Foundation (https://soulsbyfoundation.org/) and the BMZ One Health Research Education & Outreach Centre in Africa (OHRECA). EF, JR, and OH are also part of the One Health Network for the Horn of Africa (HORN) project, which receives funding from UK Research and Innovation (UKRI) and the Biotechnology and Biological Sciences Research Council (BBSRC) (project number BB/P027954/1). Open access publication fees are supported by the University of Liverpool institutional access fund. The funders had no role in the decision to publish or the preparation of this manuscript.

ACKNOWLEDGMENTS

We thank Dr. Allan Ogendo for his expert input on the structure of disease surveillance in Kenya. We are grateful to all our research participants for their willingness to be involved in the research, the Ministry of Health, Directorate of Veterinary Services and County Governments of Busia, Bungoma, and Kakamega for permitting us to conduct this research and the whole ZooLinK team for their support in the field.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.658454/full#supplementary-material

Supplementary Material 1 | Interview guide.

REFERENCES

1. Babo Martins S, Rushton J, Stärk K. Economic assessment of zoonoses surveillance in a "One Health"context: a conceptual framework. *Zoonoses public Health.* (2016) 63:386–95. doi: 10.1111/zph.12239
2. Severin, L. Added value of the One Health approach during the investigation and response to an outbreak of the Monkeypox epidemic among chimpanzees in Cameroon. In: *6th World ONE Health Congress* Edinburgh/Virtual (2020).
3. Rushton J, Häsler B, De Haan N, Rushton R. Economic benefits or drivers of a"One Health"approach: Why should anyone invest? *Onderstepoort J Vet Res.* (2012) 79:75–9. doi: 10.4102/ojvr.v79i2.461
4. Stärk KD, Kuribrena MA, Dauphin G, Vokaty S, Ward MP, Wieland B, et al. One health surveillance–more than a buzz word? *Prev Vet Med.* (2015) 120:124–30. doi: 10.1016/j.prevetmed.2015.01.019
5. Martins SB. *Economic Assessment of Surveillance in a'One Health' Context*. London: University of London Royal Veterinary College (2017).
6. Gibbs EPJ. The evolution of one health: a decade of progress and challenges for the future. *Vet Rec.* (2014) 174:85–91. doi: 10.1136/vr.g143
7. Spencer J, McRobie E, Dar O, Rahman-Shepherd A, Hasan N, Hanefeld J, et al. Is the current surge in political and financial attention to one health solidifying or splintering the movement? *BMJ Global Health.* (2019) 4:e001102. doi: 10.1136/bmjgh-2018-001102
8. Salyer SJ, Silver R, Simone K, Behravesh CB. Prioritizing zoonoses for global health capacity building—themes from One Health zoonotic disease workshops in 7 countries, 2014–2016. *Emerg Infect Dis.* (2017) 23(Suppl. 1):S55. doi: 10.3201/eid2313.170418
9. World Health Organization. *International Health Regulations (2005).* Geneva: World Health Organization (2008).
10. Nuttall I, Miyagishima K, Roth C, de La Rocque S. The United Nations and one health: the international health regulations and global health security. *Rev Sci Tech*. (2014). 33:659–68. doi: 10.20506/rst.33.2.2303
11. ILRI. One *Health Directory for Sub-Saharan Africa.* (2020). Available online at: http://bit.ly/ohafrica
12. Khan MS, Rothman-Ostrow P, Spencer J, Hasan N, Sabirovic M, Rahman-Shepherd A, et al. The growth and strategic functioning of one health networks: a systematic analysis. *Lancet Planet Health.* (2018) 2:e264–73. doi: 10.1016/S2542-5196(18)30084-6
13. Mbabu M, Njeru I, File S, Osoro E, Kiambi S, Bitek A, et al. Establishing a one health office in Kenya. *Pan Afr Med J.* (2014) 19:4588. doi: 10.11604/pamj.2014.19.106.4588
14. Zoonotic Disease Unit. *National One Health Strategic Plan 2012-2017, L. Ministry of Agriculture, Fisheries and Irrigation, Editor.* (2012). Nairobi: Zoonotic Disease Unit.
15. Munyua P, Bitek A, Osoro E, Pieracci EG, Muema J, Mwatondo A, et al. *Prioritization of Zoonotic Diseases in Kenya. PLoS ONE.* (2016). 11:e0161576. doi: 10.1371/journal.pone.0161576
16. Munyua PM, Njenga MK, Osoro EM, Onyango CO, Bitek AO, Mwatondo A, et al. Successes and challenges of the One Health approach in Kenya over the last decade. *BMC Public Health.* (2019) 19:465. doi: 10.1186/s12889-019-6772-7
17. Bitek AO, Osoro E, Munyua PM, Nanyingi M, Muthiani Y, Kiambi S, et al. A hundred years of rabies in Kenya and the strategy for eliminating dog-mediated rabies by 2030. *AAS Open Res.* (2019) 1:23. doi: 10.12688/aasopenres.12872.2
18. Government of Kenya. *National Action Plan for the Prevention and Containment of Antimicrobial Resistance*. Mo H, editor. Nairobi: Government of Kenya (2017).
19. Government of Kenya. *The Constitution of Kenya: 2010*. Laws of Kenya: Chief Registrar of the Judiciary (2013).
20. Government of Kenya. County Governments Act. In: Attorney-General, Editor. *Laws of Kenya No. 17 of* 2012. Nairobi: National Council for Law Reporting (2012).
21. Stärk K, Martins SB, Rushton J, Häsler B. Surveillance without intervention: is there a value. In: *15th Veterinary Epidemiology and Economics ISVEE* (Chiang Mai) (2018).
22. Bordier M, Uea-Anuwong T, Binot A, Hendrikx P, Goutard FL. Characteristics of one health surveillance systems: a systematic literature review. *Prev Vet Med*. (2018) 181:104560. doi: 10.1016/j.prevetmed.2018.10.005
23. Falzon LC, Alumasa L, Amanya F, Kangethe EK, Kariuki S, Momanyi K, et al. One health in action: operational aspects of an integrated surveillance system for zoonoses in Western Kenya. *Front Vet Sci.* (2019) 6:252. doi: 10.3389/fvets.2019.00252
24. de Glanville W, Thomas L, Cook EA, B.d.Bronsvoort C, Wamae N, Kariuki S, et al. Household socio-economic position and individual infectious disease risk in rural Kenya. *Sci Rep.* (2019) 9:1–9. doi: 10.1038/s41598-019-39375-z
25. 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
26. Kenya National Bureau of Statistics. K*enya Population and Housing Census Volume I: Population by County and Sub-County*. Nairobi: Kenya National Bureau of Statistics (2019).
27. Smolinski MS, Crawley AW, Olsen JM, Jayaraman T, Libel M. Participatory disease surveillance: engaging communities directly in reporting, monitoring, and responding to health threats. *JMIR Public Health Surv.* (2017) 3:e62. doi: 10.2196/publichealth.7540

28. Mukulu E. Perceived organisational barriers to women career progression in Kenya's civil service. *Int J Adv Manag Eco.* (2012) 1:203–13. Available online at: http://hdl.handle.net/123456789/1217
29. Wong L. *Data Analysis in Qualitative Research: A Brief Guide to Using NVivo. Malay Family Phys.* (2008) 3:14.
30. Food and Agriculture Organization of the United Nations. *Surveillance Evaluation Tool (SET) Report*. Nairobi (2018).
31. World Health Organization. *Joint External Evaluation of IHR Core Capacities of the Republic of Kenya*. Geneva: World Health Organization (2017).
32. Karimuribo ED, Sayalel K, Beda E, Short N, Wambura P, Mboera LG, et al. Towards one health disease surveillance: the Southern African Centre for infectious disease surveillance approach. *Onderstepoort J. Vet. Res.* (2012) 79:31–7. doi: 10.4102/ojvr.v79i2.454
33. Karimuribo ED, Mutagahywa E, Sindato C, Mboera L, Mwabukusi M, Njenga MK, et al. A smartphone app (AfyaData) for innovative one health disease surveillance from community to national levels in Africa: intervention in disease surveillance. *JMIR Public Health Surveillance.* (2017) 3:e94. doi: 10.2196/publichealth.7373
34. Bastiaensen P, Schneider H, d'Alessio F. *PVS Gap Analysis Report.* Paris: World Organisation for Animal Health (2011).
35. Ilukor J. Improving the delivery of veterinary services in Africa: Insights from the empirical application of transaction costs theory in Uganda and Kenya. *Rev Sci Tech*. (2017) 36:279–89. doi: 10.20506/rst.36.1.2628
36. Perez AM, Linhares DC, Arruda AG, VanderWaal K, Machado G, Vilalta Sans C, et al. Individual or common good? Voluntary data sharing to inform disease surveillance systems in food animals. *Front Vet Sci.* (2019) 6:194. doi: 10.3389/fvets.2019.00194
37. Benin S, Yu B. *Trends in Public Agricultural Expenditures in Africa*. Washington, DC: International Food Policy Research (2013).
38. World Health Organization. *Public Financing for Health in Africa: from Abuja to the SDGs*. Geneva: World Health Organization (2016).
39. Hassan SM Simiyu E. *Public Financial Management Practices Effect on Budgetary Absorption in Madera County Kenya*. Nairobi: Kenyatta University (2013).
40. Odhiambo A. Devolution Score Card after 1st Term: Achievements, Drawbacks and Way Forward. In: *26th Economic Symposium*. Nairobi: Office of the Controller of Budget: Safari Park Hotel (2018).
41. Cleaveland S, Lankester F, Townsend S, Lembo T, Hampson K. Rabies control and elimination: a test case for One Health. *Vet Rec.* (2014) 175:188–93. doi: 10.1136/vr.g4996
42. World Bank. *Decision Time: Spend More or Spend Smart*? *Kenya Public Expenditure Review*. Nairobi (2014).
43. Xu K, Soucat A, Kutzin J, Brindley C, Vande Maele N, Toure H, et al. *Public Spending on Health: A Closer Look at Global Trends*. Geneva: World Health Organization (2018).
44. Halliday JE, Hampson K, Hanley N, Lembo T, Sharp JP, Haydon DT, et al. Driving improvements in emerging disease surveillance through locally relevant capacity strengthening. *Science.* (2017) 357:146–8. doi: 10.1126/science.aam8332
45. Halliday J, Daborn C, Auty H, Mtema Z, Lembo T, Barend M, et al. Bringing together emerging endemic zoonoses surveillance: shared challenges a common solution. *Phil Trans R Soc B.* (2012) 367:2872–80. doi: 10.1098/rstb.2011.0362
46. Government of Kenya. *Agriculture Sector Development Strategy 2010-2020*, *L. Ministry of Agriculture, Fisheries and Irrigation*. Nairobi (2010).
47. Government of Kenya, *Towards Sustainable Agricultural Transformation Food Security in Kenya: 2019-2024 National Agriculture Investment Plan L. Ministry of Agriculture, Fisheries and Irrigation, Editor.* Nairobi (2019).
48. County Government of Busia. *County Integrated Development Plan 2018-2022*. Busia (2018).
49. County Government of Bungoma. *County Integrated Development Plan 2018–2022*. Bungoma (2018).
50. County Government of Kakamega. *County Integrated Development Plan 2018–2022*. Kakamega (2018).
51. 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. *Bull World Health Organ.* (2003) 81:867–76.
52. Häsler B, Cornelsen L, Bennani H, Rushton J. A review of the metrics for one health benefits. *Rev Sci Tech.* (2014) 33:453–64. doi: 10.20506/rst.33.2.2294
53. Bordier M, Delavenne C, Nguyen DTT, Goutard FL, Hendrikx P. One health surveillance: a matrix to evaluate multisectoral collaboration. *Front Vet Sci.* (2019) 6:109. doi: 10.3389/fvets.2019.00109
54. Rüegg SR, Häsler B, Zinsstag J. *Integrated Approaches to Health: A Handbook for the Evaluation of One Health.* Wageningen Academic Publishers (2018). doi: 10.3920/978-90-8686-875-9
55. Belot G, Caya F, Errecaborde K, Sreedharan R, Traore T, Lafia B, et al. IHR-PVS National Bridging Workshops, a tool to operationalize the collaboration between human and animal health while advancing sector-specific goals in countries. *bioRxiv*. (2020). doi: 10.1101/2020.12.29.424658. [Epub ahead of print].

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.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 01 July 2021
doi: 10.3389/fvets.2021.647838

Risk of Introduction of Classical Swine Fever Into the State of Mato Grosso, Brazil

Daniella N. Schettino[1,2], Fedor I. Korennoy[3] and Andres M. Perez[1]*

[1] Department of Veterinary Population Medicine, Center for Animal Health and Food Safety, College of Veterinary Medicine, University of Minnesota, St. Paul, MN, United States, [2] Animal Health Coordination, Instituto de Defesa Agropecuária de Mato Grosso (INDEA-MT), Mato Grosso, Cuiabá, Brazil, [3] FGBI Federal Centre for Animal Health (FGBI ARRIAH), Vladimir, Russia

Classical swine fever (CSF) is considered one of the most important diseases of swine because of the far-reaching economic impact the disease causes to affected countries and regions. The state of Mato Grosso (MT) is part of Brazil's CSF-free zone. CSF status is uncertain in some of MT's neighboring States and countries, which has resulted in the perception that MT is at high risk for the disease. However, the risk for CSF introduction into MT has not been previously assessed. Here, we estimated that the risk for CSF introduction into the MT is highly heterogeneous. The risk associated with shipment of commercial pigs was concentrated in specific municipalities with intense commercial pig production, whereas the risk associated with movement of wild boars was clustered in certain municipalities located close to the state's borders, mostly in northern and southwestern MT. Considering the two pathways of possible introduction assessed here, these results demonstrate the importance of using alternative strategies for surveillance that target different routes and account for different likelihoods of introduction. These results will help to design, implement, and monitor surveillance activities for sustaining the CSF-free status of MT at times when Brazil plans to expand the recognition of disease-free status for other regions in the country.

Keywords: classical swine fever, risk assessment, domestic pigs, wild boars, Mato Grosso, Brazil

OPEN ACCESS

Edited by:
Carola Sauter-Louis, Friedrich-Loeffler-Institute, Germany

Reviewed by:
Hsin-Yi Weng, Purdue University, United States
Rachel Anne Taylor, Animal and Plant Health Agency, United Kingdom

****Correspondence:***
Daniella N. Schettino
donas001@umn.edu

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: *30 December 2020*
Accepted: *28 May 2021*
Published: *01 July 2021*

Citation:
Schettino DN, Korennoy FI and Perez AM (2021) Risk of Introduction of Classical Swine Fever Into the State of Mato Grosso, Brazil. Front. Vet. Sci. 8:647838. doi: 10.3389/fvets.2021.647838

INTRODUCTION

Classical swine fever (CSF), also referred to as hog cholera, is arguably one of the most important viral diseases affecting domestic and wild swine, and for that reason, the disease is notifiable to the World Animal Health Organization (OIE). The CSF's impact on the swine industry is associated with the mortality and reduction of productivity caused by the disease, and, most importantly, with disease-related trade restrictions, which results in important economic and social consequences for infected areas (1–3). CSF is caused by an enveloped RNA virus of the genus *Pestivirus* of the family Flaviviridae referred to as CSF virus (CSFv). The most common routes for CSF spread include oronasal transmission through direct or indirect contact with infected pigs, consumption of pig meat infected with the virus, and vertical transmission from an infected sow to her offspring (4–6).

Sixteen (15 states and 1 federal district) of the 27 administrative units of Brazil have been recognized by the OIE as CSF-free since May 2016; those 16 administrative units constitute the majority of the country's national pig production. The state of Mato Grosso (MT) is the fifth largest pig producer in the country, with 2,590,872 heads corresponding to approximately 8.7%

of the Brazilian pig herd and is located in the CSF-free zone of Brazil. Most (n = 1,933,248 pigs, 74.6%) of MT's pig population is concentrated at 1.3% (n = 550) of the premises registered as commercial pig farms in the state, whereas the remaining 657,624 (25.4%) pigs are located in 43,398 backyard (subsistence) farms (7). There are also seven multiplier farms in MT, and commercial operations are divided into farrow-to-finish, sow, and finishing farms. Commercial pig farms are highly concentrated in municipalities at the central-northern region of the state. Although CSF has never been reported in MT, the state is adjacent to the non-CSF-free zone of Brazil in the north (states of Amazonas and Para) and Bolivia (where the CSF status is uncertain) in the southwest. For that reason, there is a perception among MT swine producers that the state is at high risk for the introduction of CSFv. Additionally, the last CSF outbreaks reported in Brazil (2009 and 2018/2019/2020) affected backyard pig farms in the non-CSF-free zone (8) increasing concerns among swine farmers in the CSF-free area.

Free roaming of CSF-infected wild boars, which are considered an exotic and intruder species in the Brazilian territory (9), may result in the introduction of CSF into MT. Additionally, although the movement of pigs and pork products is only allowed between states in the CSF-free zone, the CSF-free zone is quite extensive and includes a number of Brazilian States. For that reason, if an outbreak occurs in a state other than MT, there are chances that infected pigs may be moved into MT prior to the time of outbreak detection, when animal movements would be banned.

Risk assessment is an epidemiological tool frequently used by countries to assess the risk for transboundary animal diseases (TADs) such as CSF, African swine fever (ASF), and foot-and-mouth disease (FMD). Many studies have been developed to assess the risk of introduction of these diseases into free areas, mostly through movement of live animals or animal products as part of international trade, which is one of the reasons for performing risk assessments according to the OIE. In the early 2000s, most published risk assessments were related to FMD and CSF and considered pathways such as pig movement, pig products (semen, pork), and fomites (2, 10–12). After the incursion of ASF into Georgia in 2007, many risk assessments were performed for ASF introduction into free areas, and wild boars started to be included as potential pathways (13–16). Risk assessments are most frequently performed at the national level to propose risk mitigation actions associated with international contacts, but for countries in which regulations are implemented by states rather than federal governments, such as Brazil, there are also benefits in estimating the risk at the subnational level (12).

The objective of the study here was to rank MT municipalities in terms of their risk for CSFv introduction, either through wild boar movements or through legal movement of commercial pigs, and to compare those ranks to evaluate the correlation at the municipality-level risk of entry through those two pathways. The results will help to inform the design of surveillance strategies and allocation of resources in MT with the ultimate objective of preventing or early detection of a hypothetical introduction of CSFv into the State.

MATERIALS AND METHODS

General Approach

The risk for CSFv introduction into MT through two alternative pathways, namely, (i) the movement of live pigs assuming a hypothetical CSF outbreak in the CSF-free zone of Brazil and (ii) free ranging of wild boars, described in the following sections, was assessed at the state and municipality levels in MT. Municipalities were subsequently ranked in terms of the risk associated with each pathway, and ranks were compared to evaluate the correlation between pathways.

CSFv Introduction Through Movement of Live Pigs—Assessing Risk for Commercial Farms

Animal Data Sources

Official data from MT's Official Veterinary Service (INDEA/MT) regarding the legal movement of pigs into MT from 2016 through 2018 were used (7). All shipments originated from CSF-free states, given that pig movements from non-CSF-free states are banned, were retrieved from the INDEA/MT database. Movements for slaughtering and/or fair purposes were screened out because slaughter is a dead end for disease transmission, and pig fairs are rare in MT. Subsequently, only between-farm movements were considered for the analysis.

Analytical Framework

A stochastic risk assessment model was fitted to estimate the probability of introduction of CSFv into MT *via* movement of live pigs during a 1-year time period, which was assessed both at the state and municipality levels. For the estimate of risk at the state level, we considered the total number of pigs that were shipped to MT from the states that are part of the CSF-free zone and, hence, allowed to trade with MT, given the hypothetical scenario of one undetected epidemic on the CSF-free zone of Brazil. For the probability of introducing the disease into any municipality of MT, we considered the number of animals that were shipped into each municipality of MT. The annual risk for CSF introduction into MT farms through pig movements (Rpm) was quantified assuming a binomial model of the form

$$Rpm = 1 - (1 - Psm\,)^{Nsm}$$

where Nsm is the number of pigs shipped from the CSF-free zone into each municipality m of MT before detection of the outbreak in the free zone; for the estimates at the state level, the total number of pigs shipped into MT was used. Psm was the probability of introduction of one infected animal. The value of Psm was the same for each municipality m and for the state of MT, and it was computed as the product of four conditional probabilities (P1–P4) describing the nodes of the risk pathway, which were modeled in a scenario tree (10, 13, 17). Nodes were parameterized (**Table 1**) following principles explained in detail elsewhere for selecting distributions (21), and the approach was similar to risk assessments done for the introduction of CSF (11) and FMD (2) in Spain, and ASF (13) in the European Union.

The first node (P1) of the scenario tree (22) was the probability of importing an infected commercial pig from the CSF-free zone

TABLE 1 | Parameterization of a quantitative assessment of the risk of introduction of classical swine fever (CSF) into the state of Mato Grosso (MT), *via* legal movement of pigs and assuming a CSF outbreak in the disease free-zone of Brazil.

Input	Parameter	Distribution	Value	Source of information
Population of commercial pigs in free zone (NT)	NT	Normal	μ^*: 22,758,504 σ^{**}: 1,529,008.972	Database MAPA-BR (18)
Total number of commercial farms—herd number (NH)	NH	Normal	μ^*: 25,902 σ^{**}: 784.621	Database MAPA-BR (18)
Average herd size (H)	H	Equation	NT/NH	Model equation
Intraherd prevalence (IP)	IP	Pert	Min: 0.05 Most likely: 0.4 Max: 1	Martínez-López et al. (11)
Expected undetected outbreaks (EO)	EO	Pert	Min:1 Most likely: 6 Max: 39	Martínez-López et al. (11)
Number of pigs in free zone expected to be infected before the detection of the outbreak (NI)	NI	Equation	IP * H * EO	Model equation
Probability of importing an infected commercial pig from free zone (assuming an outbreak before detection) (P1)	P1	Beta	$\alpha 1 = NI + 1$ and $\alpha 2 = NT - (NI + 1)$	Adapted from Martínez-López et al. (11); Database MAPA-BR (18)
Probability of infected pig surviving the infection (P2)	P2	Pert	Min: 0.63 Most likely: 0.78 Max: 0.932	Martínez-López et al. (11)
Probability of infected pig surviving shipment (P3)	P3	Pert	Min: 0.908 Most likely: 0.9973 Max: 0.9995	Murray and Johnson (19)
Probability of quarantine in destination (Pq)	Pq	Beta	$\alpha 1 = 130.71$ and $\alpha 2 = 15.41$	Martínez-López et al. (2); Martínez-López et al. (11)
Probability of detection during quarantine (Pd)	Pd	Beta	$\alpha 1 = 1.33$ and $\alpha 2 = 34.16$	Martínez-López et al. (11); Mur et al. (13)
Probability of non-detection of infected animal at destination and of animal establishing contact with susceptible in MT farm (P4)	P4	Equation	1 – Pq * Pd	Martínez-López et al. (11); Mur et al. (13)
Time of detection in days (Td)	Td	Pert	Min: 11 Most likely: 40 Max: 127	Bronsvoort et al. (10), Pineda et al. (20), and OIE -WAHIS (8)
Number of pigs shipped to MT (and to each municipality m)	*n*	Poisson-lognormal	μ^* and σ^{**} of number of pigs sent from states s to MT [and each municipality of destination *m* (2016–2018)]	INDEA/MT database (7)

**Mean, **standard deviation.*

during the silent phase of the epidemic, i.e., before detection of the Official Veterinary Service (OVS) in the origin (the CSF-free zone of Brazil). A beta distribution was used to calculate this probability, of the form $\alpha 1 = NI + 1$ and $\alpha 2 = NT - (NI + 1)$, where NI is the "*Number of pigs, expected to be infected in the free-zone before the detection of the outbreak*," and NT is the "*Population of commercial pigs in the CSF-free zone (NT).*" The calculation of these parameters is described later in this section.

The second and third nodes, denoted as P2 and P3, were the probabilities that the infected pig survived infection and shipment, respectively, for which we used a Pert distribution parameterized with data extracted from the literature (2, 11).

The last node of the scenario tree (P4) represented the probability that an infected imported pig established contact with a susceptible pig in a farm in MT, causing a CSF outbreak, i.e., assuming a failure of quarantine and detection by OVS at the municipality of destination *m*. This probability was calculated as 1 – Pq * Pd, where Pq is the probability of quarantining the animal at the destination, and Pd is the probability of detecting the disease during that quarantine (11, 23).

For the calculation of the "*population of commercial pigs in free zone (NT)*" variable, we used a normal distribution (normal μ, σ), considering as mean (μ) the total number of pigs in commercial pig farms at the CSF-free zone in 2017, except MT, and σ is the standard deviation of the total number of commercial pigs at the CSF-free zone during the period 2014–2017. This input was one of the components used to calculate P1. Data required to estimate the parameter NT was obtained from the Brazilian Ministry of Agriculture, Livestock and Food Supply (MAPA/BR) (18).

Values for the "*total number of commercial farms - herd number (NH)*" variable were calculated using a normal distribution (normal μ, σ), considering as mean (μ) the total number of commercial pig farms at the CSF-free zone in 2017, and σ is the standard deviation of the total number of commercial pig farms in the period 2014–2017. This input was used to calculate the average herd size (H). Data required to estimate the parameter NH were obtained from the Brazilian Ministry of Agriculture, Livestock and Food Supply (MAPA/BR) (18).

The variable "*Number of pigs, expected to be infected in the free-zone before the detection of the outbreak (NI)*" was calculated by the equation IP * H * EO, where intraherd prevalence (IP), the average herd size in the CSF-free zone (H), and the number of expected undetected outbreaks at the origin (EO) were multiplied to generate the number of pigs expected to be infected at the CSF-free zone during an outbreak in the silent phase (NI), that is, before the detection of the index case of CSF by the OVS in the origin (11). The parameters *average herd size (H)*, *intraherd prevalence (IP)*, *and expected undetected outbreaks (EO)* were calculated as explained in the following paragraphs.

Because states in the CSF-free zone have the same sanitary status regarding CSF, and they are allowed to trade pigs between them, we assumed the CSF-free zone as one single unit, whereas the risk for introduction of CSF was stratified for each municipality of destination *m*. The *average herd size (H)* was approximated as the *NT/NH* ratio in the CSF-free zone.

The "*intra-herd prevalence (IP)*" was calculated using a Pert distribution; although the incubation period of CSF is generally 4–10 days, under field conditions, CSF is expected to show unspecific symptoms at the beginning of an outbreak, which can delay the detection of infected herds in 2–4 weeks, increasing the intraherd prevalence at the moment of detection by the OVS (24, 25).

The "*expected undetected outbreaks (EO)*" is defined as the number of herds that would be infected by the time when a hypothetical epidemic in the CSF-free zone was detected and pig movements into MT banned. EO was assumed to follow a Pert distribution with a minimum of one undetected outbreak (the index case), and the most likely and maximum equal to the number of herds that were affected before the detection of the CSF epidemics in Spain in 2001, and in The Netherlands in 1997, respectively (11).

To adjust the number of pigs that would be sent to MT between the beginning and detection of the outbreak in the CSF-free zone, we estimated the *time-to-detection (Td)*, i.e., the length in days before the epidemic is detected, and movements into MT are banned. Under field conditions, the detection is expected to take longer than the incubation period. A Pert distribution was used for modeling *Td*, with the minimum, most likely, and maximum values being those reported in Colombia, in Ceará (a state of Brazil in the CSF non-free zone in which outbreaks occurred in 2018), and the recommendation of the European Union on the parameter that should be used when there is no information available, respectively (8, 10, 20).

The number of pigs that were shipped from the CSF-free zone was estimated considering the number of pigs that came from states *s* into MT and into each municipality *m* of MT during the years 2016–2018. For each municipality of destination *m* during the period of the study, we grouped the movement from 2016 to 2018 and computed the mean (μ) and standard deviation (σ) of the total number of pigs that were sent to each municipality *m* from states of origin *s*, during this period (7). Then, the number of pigs annually shipped into MT and into each municipality m (n) from the CSF-free zone was assumed to follow Poisson-lognormal distributions, with mean (μ) and standard deviation (σ) estimated for MT and for each municipality *m*, respectively. The number of pigs that each municipality *m* of MT received is listed in the **Supplementary Material**. The number of pigs that would be shipped from the CSF-free zone before detection of the outbreak in the free zone (N*sm*) was subsequently computed for MT and for each municipality *m* as the number of pigs shipped per day (n/365) multiplied by the time-of-detection (in days) of an outbreak in the CSF-free zone (Td), so that:

$$Nsm = (n/365)^{*}\ Td.$$

A spider graph was generated in Excel to evaluate what parameters (**Table 1**) mostly contributed to changes in the mean risk for the introduction of CSF into MT, i.e., assessing the sensitivity of the model to the uncertainty and variability associated with its parameterization. For that sensitivity analysis, we selected the first (Q1), second (median—Q2), and third quartile (Q3) for the distribution of each parameters evaluated, i.e., P1, P2, P3, P4, Td, and *n*. The median was the measure of central tendency, and Q1 and Q3 were measures of dispersion. We systematically calculated the final risk probability with different situations for each parameter at a time when the others were kept fixed in the median (second quartile) as the central tendency.

Computational Environment and Software

The stochastic model was implemented in the @Risk 8.0 software (26) and run through 10,000 iterations. Results were spatially visualized using Arc GIS version 10.5.1 (27).

CSFv Introduction Into MT Through Wild Boars—Assessing Risk for Backyard Farms

Animal Data Sources

Pig farms registered in the INDEA/MT database by July 2019 were retrieved, including data on type of farms (subsistence, commercial), their geographic location, and the total number of pigs per farm (7).

Additionally, data regarding active surveillance activities for CSF in MT pig farms from 2016 to 2018 were retrieved to determine the presence or absence of free-range wild boars at those premises. Records of visits were organized in a dataset, and records repeated on any given farm were removed manually. Presence of wild boars was reported in 1,688 (24.7%) of the 6,827 visited farms (7). Data were used to estimate the distribution of wild boars fitting a maximum entropy (MaxEnt) model and procedures described elsewhere (28). Briefly, farms in which wild boars were reported were geolocated. Then, data on 27 environmental layer variables assumed to influence the presence of wild boar population in MT were retrieved, including 19 rasters from the WorldClim online database for the period 1970–2000 at a spatial resolution of 5 arc-min (∼10 km). These variables (WorldClim) are derived from records of temperature and precipitation. Consequently, it is possible for at least some of those 19 variables to be highly correlated with each other, potentially leading to issues with colinearity; for those reasons, there is a need to remove highly correlated variables from the final model (29). The human influence or anthropogenic impact was approximated using the human footprint raster obtained from the Socioeconomic Data and Applications Center from Wildlife Conservation (WCS) and Center for International Earth Science Information Network (CIESIN)—Columbia University. The global footprint raster is a global dataset of 1-km grid cells, created from nine global data layers covering human population pressure (population density), human land use and infrastructure, and human access (30). The variable altitude/elevation data (referred to as SRTM) were extracted using DIVA-GIS, which is a free computer program for mapping and geographic data analysis with ready-to-use downloading raster. SRTM stands for Shuttle Radar Topography Mission (SRTM), and it is a 3 arc, i.e., 30 s of resolution, raster created with data from the National AeroSpatial Agency (NASA) representing a near-global set of land elevations (31). For the variable land cover, vegetation, crops, temperature, and isothermality, raster data were extracted from IPUMS Terra—Integrated Population and Environmental data, which is a global-scale framework data that allowed extraction data by country level (Brazil) (32). The vegetation index was extracted as a product of MODIS Land Cover, which is produced by NASA, and from this was selected the specific vegetation index for MT with a 250-m resolution (33). The global total irradiation was acquired by downloading a raster data from Global Solar Atlas, which is published by the World Bank Group, and prepared by Solargis, with a resolution of 250 m (34). Our choice of final variables was ultimately determined by the procedure of reducing multicolinearity but keeping variables that make sense for the purpose of detecting the wild boar population distribution in MT. Thus, a colinearity diagnostic was performed to screen out highly correlated environmental variables. The redundant variables were identified by the Raster package in R studio (35) and removed from the model if the meaning of the variable would not hamper the final model. Subsequently, only 15 environmental variables were used in the model (**Table 2**). The prediction value generated by each geographic coordinate was summed by each polygon, which were the 141 municipalities of MT. Then, these set of values were separated by the median, and the values were set as 50% high and 50% low density. This final information regarding the high/low density for wild boar population per each municipality of MT was included in the model generated for the risk calculation of introduction of CSF in MT *via* wild boars and explained in detail in the following section Analytical Framework.

TABLE 2 | Environmental variables used to predict the distribution of wild boars in the state of MT, using a maximum entropy (MaxEnt) model.

Type	Variable name	Description
Human influence	hfp	Human footprint. Represents the impact of humans in the environment
Climate	bio 3	Isothermality (BIO2/BIO7) (×100)
	bio 7	Temperature annual range (BIO5–BIO6)
	bio 8	Mean temperature of wettest quarter
	bio 13	Precipitation of wettest month
	bio 15	Precipitation seasonality (coefficient of variation)
	bio 18	Precipitation of warmest quarter
	bio 19	Precipitation of coldest quarter
	isotherm	Oscillations of day–night temperature comparing summer/winter
Altitude/elevation	bralt	Shuttle Radar Topography Mission (SRTM) with 3 arc seconds (30 s) of resolution
Vegetation	crop	Area used as a cropland
	landcover	Global land cover area reference
	veg	Cropland/natural vegetation mosaic
Vegetation index	sdat	The vegetation index variation from the years 2000–2001 and 2003–2004, specific for Mato Grosso
Solar incidence	gti	Global total irradiation

Analytical Framework

The assumption here was that wild boars in Bolivia and in Brazilian states outside of the CSF-free zone may carry the CSFv and pass freely through the MT borders. We also assumed that the risk at the municipality level would be influenced by the domestic pig density, wild boar density, backyard farming share, shared border with CSF-infected zone or Bolivia, road density, and human population density in the state. The values of those variables were dichotomized (high/low or yes/no). Specifically, (a) pig density was calculated as the number of pigs in each municipality divided by the area in km^2 and dichotomized using the median value (50% high, 50% low). The number of commercial pigs in the municipality was included in the computation, in addition to backyard pigs, to account for the probability of contact between backyard pigs and commercial pigs, and because backyard farming was specifically included as a separate variable, thus, accounting for that factors in the computations (36). (b) Backyard farming share was calculated as the number of backyard farms divided by the number of farms per each municipality and dichotomized using the median value (50% high, 50% low); this risk factor can play an important role in the dynamic of CSF due to low biosecurity and little interaction with veterinary services (37). Values for calculation of (a) and (b) were extracted from the database of the MT OVS (7). (c) Human density was calculated as the population estimated in the last national census conducted in 2010 (38) for each MT municipality, divided by the area (km^2) of each correspondent municipality of MT, and dichotomized using 5 habitants/km^2 as the threshold (high, low); the 5 habitants/km threshold was set up because it was the approximate midpoint between the median (2.29 habitants/km^2) and mean (6.76 habitants/km^2) densities and that resulted on an acceptable 1:3 ratio for the classification of districts as high or low density—alternatively, the use of the mean and median as cutoff values for the classification did not affect the results of the regression model (data non shown). Human density was included as a proxy for the movement of people (tourists or workers) that can carry contaminated food that can be disposed and accessed by wild boars (20, 39–41). (d) Road density was calculated using ArcGIS, considering the layers of municipalities and layers of roads of MT and dichotomized using the median (50% high, 50% low); road density was included because the introduction and spread of the disease may be influenced by human activities that could increase the risk for contacts with wild boars (37). (e) Wild boar density was estimated aggregating the results of the maximum entropy (MaxEnt) (described in the section Animal Data Sources for this pathway) prediction model at the municipality level and dichotomized using the median (50% high, 50% low). Wild boar density is important not only because of the susceptibility of wild boar to CSF infection but also because if infected, populations of wild pigs may be the primary source for CSF introduction in domestic pig herds (40). Dichotomization of the variable was required to incorporate it in the regression model and also to increase the accuracy of the MaxEnt predictions. (f) Shared border with a non-CSF-free state or country was estimated using ArcGIS and dichotomized (yes, no). The relative contribution of each variable to the final risk was assumed to be similar to the weight estimated by a panel of experts for the risk of introduction of African swine fever (ASF) into a free region from a neighboring infected country described in detail elsewhere (41). Briefly, the model approach was based on a factorial design to identify 10 representative scenarios of the combination of parameters hypothesized to influence the risk of introduction of ASF (domestic pig density, wild boar density, backyard farming share, share border to a country that is infected with ASF, road density, and human density). Each scenario was referred to as hypothetical Region A to hypothetical Region J ($n = 10$) representing different epidemiological conditions. International experts, which were chosen by snowball sampling technique after consultation with the OIE reference laboratories for ASF in Spain, the UK, and the National Reference Laboratory of the Russian Federation, were requested to rank the 10 hypothetical scenarios in terms of their likelihood of serving as a port of entry for ASF into the country, where 1 meant the lowest risk, and 10 meant the highest risk for introduction of the disease in districts of a free country, and the hypothetical scenarios were categorized by a combination of dichotomized (high/low, yes/no) risk factors listed before. An ordinal logistic regression model was fitted to estimate the relative weight that the experts implicitly gave to each of the variables (pig density, backyard farming share, human density, road density, wild boar density, and share border with a non-CSF-free region), as approximated by the value of the regression coefficients. A risk score of the introduction of CSF through wild boar (Rbm) was subsequently computed assuming an increase by factors of Rbm = β_0 + 3.39 * pig density + 4.16 * backyard farming share + 0.55 * human density + 0.67 * road density + 3.4 * wild boar density + 2.34 * share border with non-CSF-free region for municipalities categorized as high (or yes), compared with those categorized as low (or no). Rbm was computed for each of the 141 municipalities in MT as the sum of the dichotomized values of the risk predictors weighted by an increase in risk assumed for each of the factors. Finally, municipalities were ranked in terms of the computed value of Rbm.

Computational Environment and Software

The MaxEnt software (42) was used for computing the maximum entropy model of wild boar distribution. The correlation between environmental layers was conducted in RStudio Team (2019) version 3.5.3 (35) using "raster" and "rgdal" packages; the packages "MASS," "tidyverse," and "ggbeeswarm" were used in performing the ordinal logistic regression to generate the proxy-risk for introduction of CSFv in MT considering the model developed by ASF risk prediction for Kazakhstan (41). ArcGIS 10.5.1 (27) was used for spatial data processing and mapping data and results.

Correlation Between Pathways

The correlation between the two pathways for the risk of introduction of CSF into MT was computed using a Spearman correlation test (R_s) as

$$R_s = 1 - \frac{6\Sigma\,(R_i - S_i)^2}{n\left(n^2 - 1\right)}\ (43)$$

where R_i is the rank for the value x_i, which is the mean risk generated by risk assessment for the introduction of CSFv through movement of commercial pigs (Rpm), S_i is the rank for the value y_i, which is the risk score generated by the assessment for the introduction of CSFv through movement of wild boars (Rbm), and n is the number of observations, i.e., the number of municipalities in MT ($n = 141$). The correlation was implemented in the RStudio Team (35) version 3.5.3 software using the statistics base-package "cor.test (x, y, method = 'Spearman,' exact = FALSE)."

Additionally, municipalities were categorized as low or high risk for each of the two pathways assessed. For the risk of introduction through movement of live pigs, we used 0.01 as the cutoff value because values lower than that would mean that, on average, one would expect one outbreak every 100 epidemics in the CSF-free zone, which is also relatively unexpected. For that reason, values <0.01 were assumed to represent negligible risk for this pathway. For the risk of introduction through wild boars, the median was used as a cutoff value to be able to divide the municipalities of MT as the 50% low and 50% high proxy-risk, allowing a conservative comparison. Both dichotomizations were subsequently combined to group municipalities into four categories, representing high risk to both, either (two groups), or none of the pathways.

RESULTS

The risk associated with the legal movement of pigs (Rpm) was heavily concentrated, with five (3.5%) municipalities accounting for 96% of the total risk and much of the risk clustered in the central districts of MT (**Figure 1**). The risk was higher than the threshold (0.01) in only six municipalities, but it was relatively high (>0.1) in five of those six. In contrast, the risk was nil for most ($n = 89$, 63.1%) municipalities (**Figure 1**, districts in

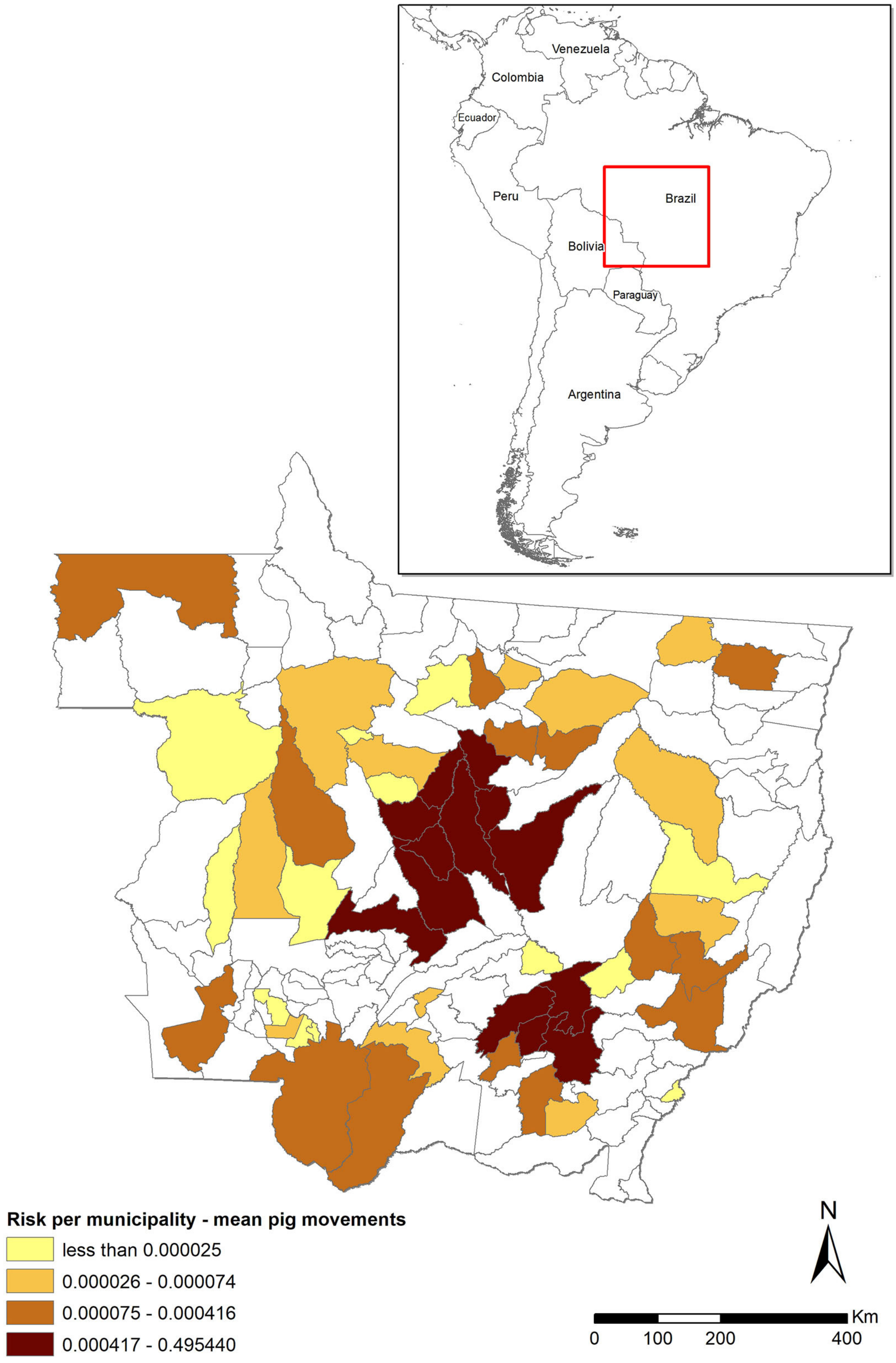


FIGURE 1 | Risk of classical swine fever (CSF) introduction into Mato Grosso (MT) through movement of pigs (Rpm) stratified by municipality and assuming an undetected outbreak in states in the CSF-free zone that ship pigs to MT. The darker the shade, the higher the risk. Municipalities in white did not receive pigs from outside MT during the assessed 3-year period. The red square shows the localization of MT in Brazil/Latin America map.

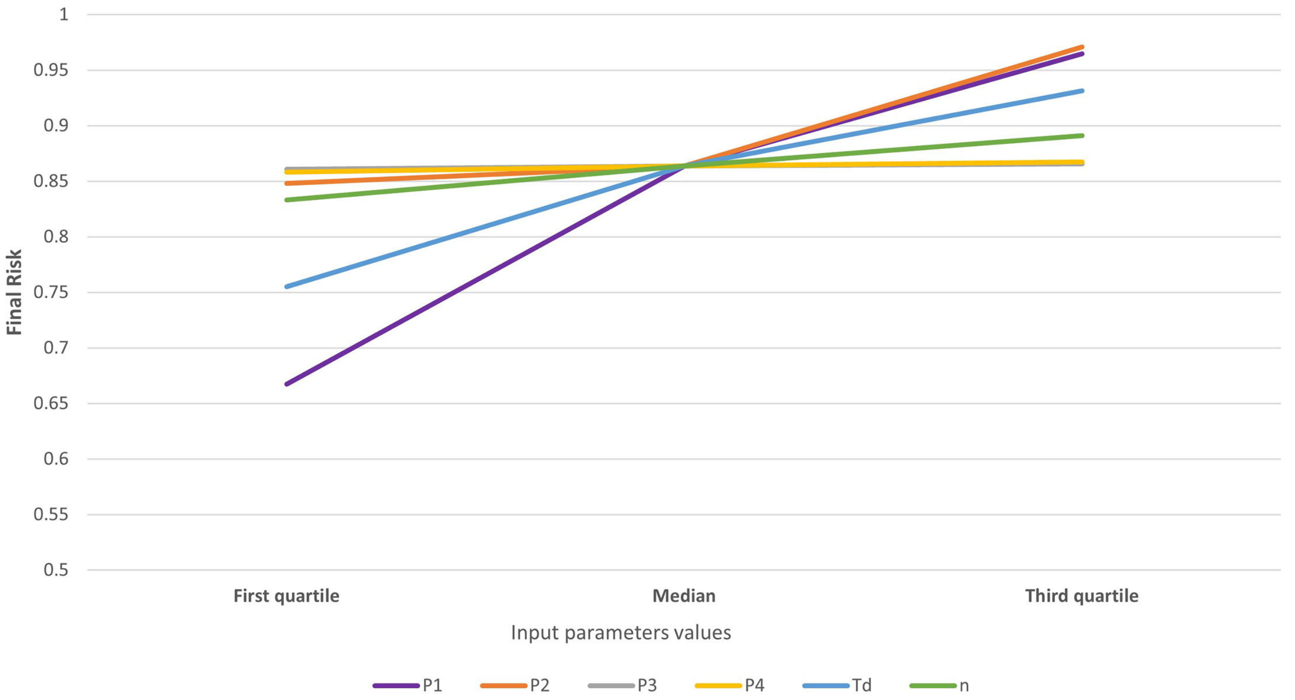


FIGURE 2 | Sensitivity to variations in the parameters of a risk assessment model for the introduction of CSF into MT. Model parameters are the probability of importing an infected pig (P1—purple line), the probability that an infected pig survives the infection before the shipment to MT (P2—orange line), the probability that an infected pig survives the shipment to MT (P3—gray line), the probability that an infected imported pig established contact with a susceptible pig in a farm in MT (P4—yellow line), the time-to-detect the outbreak (Td—blue line), and the number of pigs shipped into MT (*n*—green line).

white) because they did not receive any pigs from outside MT from 2016 through 2018. The mean risk of introduction into MT [0.763−95% CI (0.21–1.0)] suggests that, in the scenario of a hypothetical outbreak in the CSF-free zone of Brazil and assuming that time-to-detection of the first outbreak would be similar to those observed in other epidemics, it is likely that MT would suffer an outbreak. The model was most sensitive to variations in the probability of importing an infected pig (P1) and the time-to-detection of the outbreak by the OVS at the origin (Td), followed by the probability of the pigs that survive the infection (P2) and the number of pigs shipped into MT (*n*), respectively (**Figure 2**).

The maximum entropy algorithm calculated the distribution of the wild boar population in MT using 1,048 observations of wild boar as a training data and 261 observations as a testing data from the total of 1,688 observations captured from active surveillance performed by OVS of MT from 2016 to 2018. Observations, 379, were excluded from the model due to issues with the geographic coordinates collected during the surveillance activity. The area under the curve (AUC) of the receiver operating characteristic (ROC) curve was 0.765 for testing, with 0.014 of standard deviation, which was considered an acceptable accuracy. Although wild boars were predicted to be distributed throughout the state (**Figure 3A**), most of the risk associated with CSFv introduction through free roaming of wild boars (as approximated by the value of the risk score Rbm) was concentrated in the northern and southern districts of MT (**Figure 3B**). Eight municipalities were estimated to be at the highest risk for introduction of CSF through wild boars, and these municipalities are bordering the non-CSF-free zone in the north of MT and Bolivia in the southwest (**Figure 3B**, hatched areas).

The municipality-level risk for introduction of CSFv *via* movement of domestic pigs was poorly correlated (Spearman correlation coefficient, $R_s = 0.11$, p-value $= 0.185$) with the risk associated with free roaming of wild boars. Only five municipalities (four of them located in the central part of the state) were estimated at highest risk for introduction of CSF into MT through both pathways (**Figure 4**).

DISCUSSION

The work here characterized the risk associated with, arguably, two of the most important routes for introduction of CSF into MT, Brazil. We used these results to generate maps that depicted the spatial distribution of risk and identify municipalities that are most vulnerable to each of the assessed routes. Movement of live animals is one of the main routes for disease introduction into free areas (13). Other routes of introduction of CSF, such as legal or illegal contaminated pork products, contaminated trucks due to fecal contamination, genetic material from infected pigs such as semen, and human contact due to contamination clothing (10), were not specifically assessed here, and these results were restricted to the risk associated with movement of live pigs and wild boars. For the computation of the risk associated

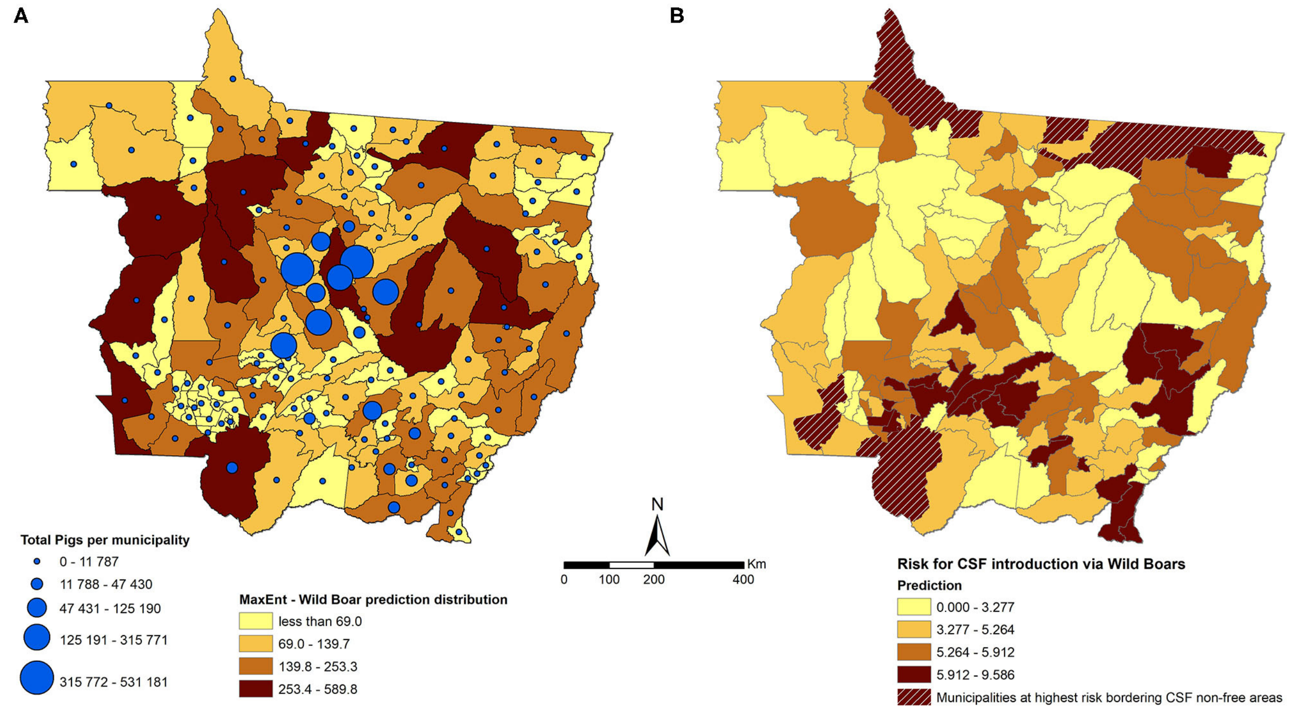


FIGURE 3 | (A) Distribution of wild boars predicted by a maximum entropy model aggregated at the municipality level in MT (the darker the shade of the polygon, the higher the predicted value) and municipality-level number of pigs (the larger the size of the blue dot, the larger the number of pigs). **(B)** Results of the model for risk scores of the introduction of CSF into MT through wild boar movement (Rbm) (the darker the polygon, the higher the risk). The hatched areas are the municipalities at highest risk bordering CSF non-free areas.

with wild boars, however, certain variables that may serve as proxy for unassessed routes, such as human and road density, were included in the model, which may have helped, in part, to account for that risk. If an outbreak occurs in the CSF-free zone, the economic impact will be devastating. In 2018, when some outbreaks in Brazil were detected in the CSF-non-free zone, the Confederation of Agriculture and Livestock of Brazil (CNA) estimated an impact of US$ 230–790 million if the infection reached the free zone of CSF in Brazil (40). For the risk assessment of introduction of CSFv in MT through movement of live pigs (Rpm), we considered a hypothetical scenario of an ongoing CSF outbreak in any other Brazilian State that is part of the CSF free-zone, with the intention to estimate the risk that MT would become infected when this occurs. The CSF-free zone is quite extensive, and the OVS of each state has its own surveillance system, which can impose variations for the time of detection outbreak, and this is a factor out of the control of MT. Ultimately, these results will help in evaluating the implementation of surveillance activities in MT and the prioritization of surveillance activities in relation to the route that imposes the highest risk for any given municipality.

The legislation that MT follows regarding CSF surveillance is dictated by the Brazilian Federal government, by which active serological surveillance is conducted only biannually in random backyard pig farms and in commercial farms only on months when the mortality rate exceeds the threshold for different ages or categories (44). However, the legislation does not consider the spatial heterogeneity of the risk imposed by alternative routes of entry. In states like MT, in which there are more than 40,000 registered pig farms, but only 550 of those are categorized as commercial farms, there is a need for specifying selective actions for municipalities, in alignment with the risk imposed by different routes, to complement the national regulation. For example, the correlation between the risk imposed by both routes was not significant ($R_s = 0.11$, p-value $= 0.185$), indicating that the districts estimated at highest risk for a given pathway were not at highest risk for the other route. However, because the risk for these two pathways was calculated using different methods, the raw values are not comparable. This finding is consistent with the need for enforcing different policy for districts regarding the design of surveillance and early detection strategies to prioritize practices associated with the routes that impose the highest risk to the municipality.

The Rpm, which was estimated assuming an undetected outbreak in the CSF-free zone of Brazil, was highly clustered in the central part of the State, where the largest pig farms in MT are located (**Figure 1**), with five municipalities concentrating 96% of the risk. A similar result was obtained in Spain, where risk was also concentrated in few provinces and in relation to those locations in which pig production is highly concentrated (11). Similar to a study conducted in Denmark, the risk associated with animal movements was relatively low, due to the small number

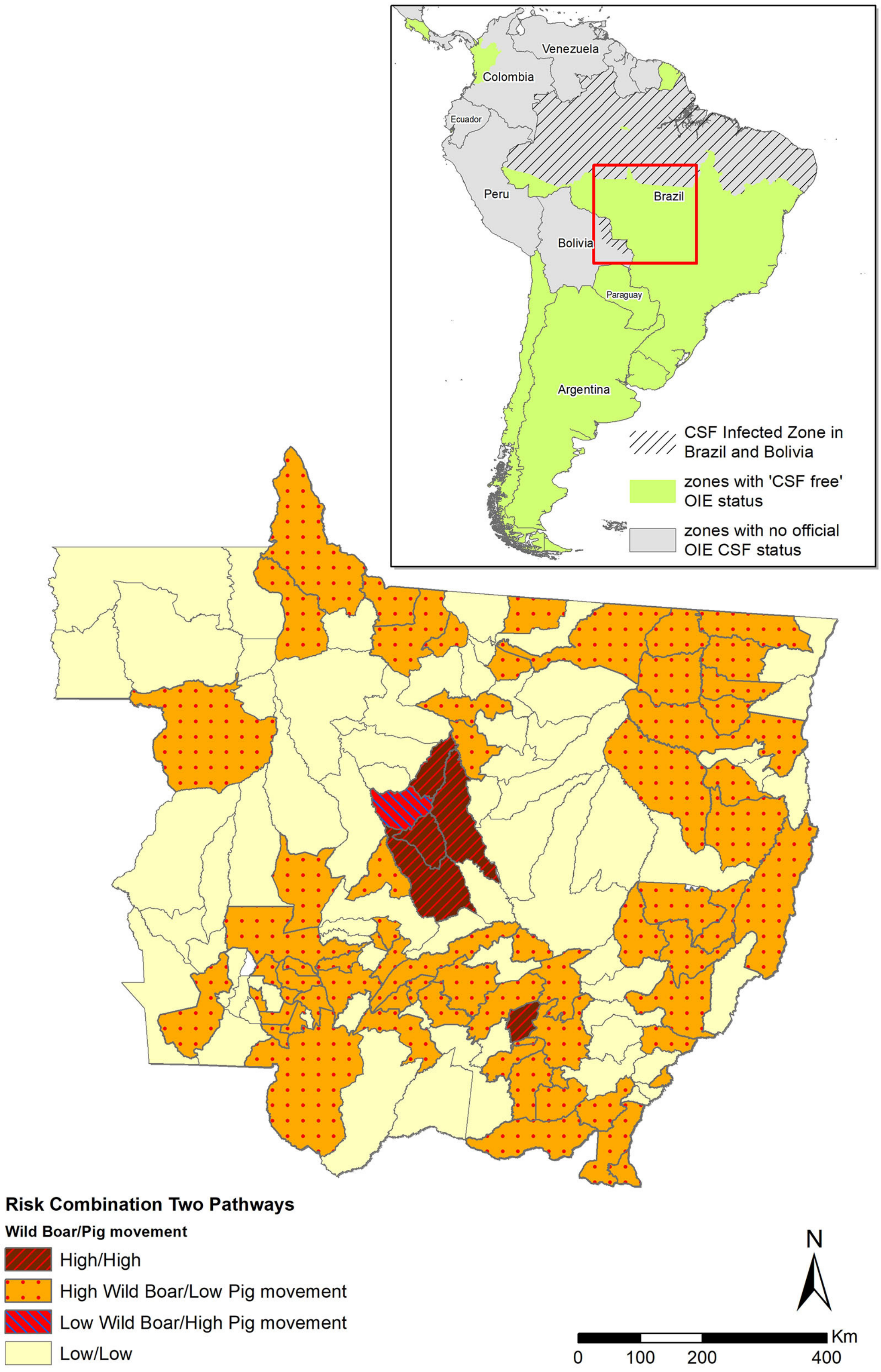


FIGURE 4 | Risk for the introduction of CSF into MT through legal movement of pigs and through free roaming of wild boars, estimated using a combination of risk analysis models. Municipalities were categorized as high risk for both pathways (brown with red hatched area), high risk for wild boars and low risk for commercial pig movements (orange with red dots), low risk for wild boars and high risk for commercial pig movements (pink with blue hatched area), and low risk for both pathways (light yellow). The green area in the Latin America map (up right corner) shows the CSF-free area recognized by OIE. The hatched gray area shows the non-CSF-free zone.

of imported pigs (10). Another study had similar results, with overall low-risk probability for introduction of ASF/CSF into the US *via* legal import of pigs and pig products, and the highest values for the probability of introduction were concentrated in three US states traditionally associated with pig production (45). In MT, only a few municipalities account for most of the pigs moved from out of the state, and only those municipalities showed high mean risk probability. Thus, targeting a relatively low number of farms in those specific municipalities, for example, through enhanced passive surveillance protocols, would help to design surveillance strategies that account for most of the risk of introduction into MT through that route.

The sensitivity analysis showed that time-to-detection (Td) highly influences the risk. Because Td is expected to be the same for all municipalities, the variability of Td is not expected to affect the ranks estimated here. However, because the variability of Td may affect the likelihood of an outbreak, the sensitivity of results to the variability of the parameter contributes to highlighting the importance of coordination and collaboration between districts in Brazil, and the impact that early detection has in the mitigation of the impact of epidemics.

Although certain municipalities at the borders were found at highest risk for the introduction through wild boars (as approximated by the value of the risk score Rbm), we found that certain municipalities at the central region of MT were also at high risk, likely because of the combination of a number of factors, such as high density of humans and pigs and the presence of wild boars that would increase risk. The model used for the calculation of the risk in this pathway may outweigh the lack of a shared border with CSF-free areas, and the model did not require a shared border with CSF-free areas to have a negligible risk from this pathway. Certainly, some believe that the biggest challenge in maintaining a free or controlled area for CSF is for the OVS to be able to enforce control and eradication measures on subsistence pig farms (4). In those municipalities, surveillance efforts may be directed toward education and outreach actions involving small holders. Those outreach and education actions may be particularly challenging in MT, given that informal reports and anecdotal evidence suggest some backyard pig owners let sows commingle with wild boars to generate the strongest offspring, which increases the risk for CSF introduction. Wild boars play an important role in the environmental maintenance of CSF and its transmission to domestic pigs. In CSFv-infected regions in which there is a high density of wild boars, a situation of endemicity may be established (6). Targeted and strategic hunting may be considered as an action to reduce wild boar population and support the implementation of a surveillance program using samples obtained from hunted animals.

Epidemic models have been increasingly used to evaluate and inform disease surveillance and control policies. For that reason, risk assessments are important tools that should be routinely incorporated by OVSs to support the design of risk-based surveillance activities (46). Quantitative assessment of the risk for CSF introduction into a country or state may help the decision-making process to ultimately prevent and control disease introduction (2). Risk assessments combining different routes of introduction broaden the scope of results, enhancing the availability of information for guiding surveillance actions (47). Noteworthy, risk assessments are formulated considering a series of limitations and assumptions, and regular updates are required to evaluate if the conditions observed when formulating the models are still valid.

In conclusion, results here indicate that the risk for introduction of CSF into MT is spatially heterogeneous, suggesting that different approaches of targeted surveillance should be implemented in the state considering, at least, two primary objectives. On one hand, there is a need for increasing the number of OVS visits to commercial farms that receive animals from outside the state, inspecting and quarantining pigs as soon as they arrive at the farm, and considering the design of passive surveillance activities targeting the early detection of CSF-like signs in those particular farms and municipalities. On the other hand, for districts in which risk was mostly associated with wild boars, actions like sampling hunted wild boars and implementation of surveillance and educational and outreach programs in backyard farms should be prioritized (37). Results here will help MT to increase the efficiency of CSF surveillance, enhancing the federal rules for CSF surveillance actions, with the ultimate objective of preventing the introduction of the disease into the State.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

DS led the data collection and analysis and wrote much of the paper. FK collaborated with the data analysis process and wrote some of the paper. AP supervised the design of the study, paper, and the data analysis process and wrote much of the paper. All authors contributed to the article and approved the submitted version.

ACKNOWLEDGMENTS

The authors would like to thank the collaboration of the Official Veterinary Service of Mato Grosso, Brazil (INDEA/MT), and the Ministry of Agriculture, Livestock and Food Supply of Brazil (MAPA) for releasing the data necessary for this study. The authors would like to thank Dr. Rachel Schambow for her help in editing the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.647838/full#supplementary-material

REFERENCES

1. Blome S, Staubach C, Henke J, Carlson J, Beer M. Classical swine fever—an updated review. *Viruses.* (2017) 9:1–24. doi: 10.3390/v9040086
2. Martínez-López B, Perez AM, De la Torre A, Rodriguez JMSV. Quantitative risk assessment of foot-and-mouth disease introduction into Spain via importation of live animals. *Prev Vet Med.* (2008) 86:43–56. doi: 10.1016/j.prevetmed.2008.03.003
3. Freitas TRP, Esteves EG, Oliveira AM, Joineau MEG, Duarte ACS, Vargas I, et al. Classical Swine Fever in Brazil: study for the survey of classical swine fever outbreaks in Brazil from 1978 to 2004. *Semin Ciencias Agrar.* (2007) 28:277–86. doi: 10.5433/1679-0359.2007v28n2p277
4. FAO, EMPRES. *Reconociendo La Peste Porcina Clássica – Manual Ilustrado.* (2003). Available online at: http://www.fao.org/3/a-y4944s.pdf (accessed April 2, 2020).
5. Penrith ML, Vosloo W, Mather C. Classical swine fever (Hog cholera): review of aspects relevant to control. *Transbound Emerg Dis.* (2011) 58:187–96. doi: 10.1111/j.1865-1682.2011.01205.x
6. Brown VR, Bevins SN. A review of African swine fever and the potential for introduction into the United States and the possibility of subsequent establishment in feral swine and native ticks. *Front Vet Sci.* (2018) 5:1–18. doi: 10.3389/fvets.2018.00011
7. INDEA/MT – Instituto de Defesa Agropecuária de Mato Grosso. *SINDESA-INDEA Database*. Available online at: http://sistema.indea.mt.gov.br:8082/SIA/logon.jsp?sys=SCA (accessed July 31, 2019).
8. OIE. *WAHIS - Animal Disease Information.* (2020). Available online at: https://www.oie.int/wahis_2/public/wahid.php/Reviewreport/Review/viewsummary?reportid=28186 (accessed January 14, 2020).
9. *Suinocultura Industrial.com.br. 6 riscos e 7 medidas de prevenção que você precisa saber sobre a PSC.* (2019). Available online at: https://www.suinoculturaindustrial.com.br/imprensa/6-riscos-e-7-medidas-de-prevencao-que-voce-precisa-saber-sobre-a-psc/20191106-110702-x320 (accessed January 7, 2020).
10. Bronsvoort BMC, Alban L, Greiner M. Quantitative assessment of the likelihood of the introduction of classical swine fever virus into the Danish swine population. *Prev Vet Med.* (2008) 85:226–40. doi: 10.1016/j.prevetmed.2008.01.013
11. Martínez-López B, Perez AM, Sánchez-Vizcaíno JM. A stochastic model to quantify the risk of introduction of classical swine fever virus through import of domestic and wild boars. *Epidemiol Infect.* (2009) 137:1505–15. doi: 10.1017/S0950268808001623
12. de Vos CJ, Saatkamp HW, Huirne RBM, Dijkhuizen AA, Saatkamp HW, Huirne RBM, et al. The risk of the introduction of classical swine fever virus at regional level in the European Union: a conceptual framework. *Rev Sci Tech.* (2003) 22:795–810. doi: 10.20506/rst.22.3.1433
13. Mur L, Martinez-Lopez B, Martinez-Aviles M, Costard S, Wieland B, Pfeiffer DU, et al. Quantitative risk assessment for the introduction of African swine fever virus into the European Union by legal import of live pigs. *Transbound Emerg Dis.* (2012) 59:134–44. doi: 10.1111/j.1865-1682.2011.01253.x
14. Mur L, Martinez-Lopez B, Costard S, de la Torre A, Jones BA, Martinez M, et al. Modular framework to assess the risk of African swine fever virus entry into the European Union. *BMC Vet Res.* (2014) 10:1–13. doi: 10.1186/1746-6148-10-145
15. Torre A de la, Bosch J, Iglesias I, Munoz MJ, Mur L, Martinez-Lopez B, et al. Assessing the risk of African swine fever introduction into the European Union by wild boar. *Transbound Emerg Dis.* (2015) 62:272–9. doi: 10.1111/tbed.12129
16. Taylor RA, Condoleo R, Simons RRLL, Gale P, Kelly LA, Snary EL. The risk of infection by African swine fever virus in European swine through boar movement and legal trade of pigs and pig meat. *Front Vet Sci.* (2020) 6:1–19. doi: 10.3389/fvets.2019.00486
17. Hernández-Jover M, Schembri N, Holyoake PK, Toribio JA, Martin PAJ. A comparative assessment of the risks of introduction and spread of foot-and-mouth disease among different pig sectors in Australia. *Front Vet Sci.* (2016) 3:85. doi: 10.3389/fvets.2016.00085
18. Ministry of Agriculture Livestock Food Supply (MAPA-BR) B. *Database of Demographic of Pig Population and Number of Pig Farms From States Located in CSF-Free Zone*. Brasilia: Ministry of Agriculture Livestock and Food Supply (2019)
19. Murray AC, Johnson CP. Impact of the halothane gene on muscle quality and pre-slaughter deaths in Western Canadian pigs. *Can J Anim Sci.* (1998) 78:543–8. doi: 10.4141/A97-122
20. Pineda P, Deluque A, Pena M, Diaz OL, Allepuz A, Casal J. Descriptive epidemiology of classical swine fever outbreaks in the period 2013-2018 in Colombia. *PLoS ONE.* (2020) 15:1–13. doi: 10.1371/journal.pone.0234490
21. Murray N, MacDiarmid SC, Wolldridge M, Gummow B, Morley RS, Weber SE, et al. *Handbook on Import Risk Analysis for Animal and Animal Products.* Vol. II. Paris: World Organisation for Animal Health (OIE) (2004).
22. Martin PAJ, Cameron AR, Greiner M. Demonstrating freedom from disease using multiple complex data sources. 1: A new methodology based on scenario trees. *Prev Vet Med.* (2007) 79:71–97. doi: 10.1016/j.prevetmed.2006.09.008
23. De Vos CJ, Saatkamp HW, Nielen M, Huirne RBM. Scenario tree modeling to analyze the probability of classical swine fever virus introduction into member states of the European union. *Risk Anal.* (2004) 24:237–53. doi: 10.1111/j.0272-4332.2004.00426.x
24. Brown VR, Bevins SN. A Review of Classical Swine Fever Virus and Routes of Introduction into the United States and the Potential for Virus Establishment. *Front Vet Sci.* (2018) 5:31. doi: 10.3389/fvets.2018.00031
25. Schulz K, Staubach C, Blome S. African and classical swine fever: similarities, differences and epidemiological consequences. *Vet Res.* (2017) 48:1–13. doi: 10.1186/s13567-017-0490-x
26. © 2019 Palisade Company L ("Palisade"). Ithaca, NY: @Risk (2020).
27. Environmental Systems Research Institute (Esri) Inc. *ArcGIS Desktop: Release 10.5.1*. Redlands, CA (2017). Available online at: www.esri.com (accessed April 1, 2020).
28. Bosch J, Mardones F, Pérez A, De la Torre A, Muñoz MJ. A maximum entropy model for predicting wild boar distribution in Spain. *Spanish J Agric Res.* (2014) 12:984–99. doi: 10.5424/sjar/2014124-5717
29. Fick SE RJH. WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. *Int J Climatol.* (2017) 37:4302–15. doi: 10.1002/joc.5086
30. Wildlife Conservation (WCS) and Center for International Earth Science Information Network (CIESIN). *Last of the Wild Data Version 2, 2005 (LTW-2): Global Human Footprint Dataset (Geographic).* (2005). Available online at: http://sedac.ciesin.columbia.edu/wildareas/ (accessed January 7, 2020).
31. DIVA-GIS. *Free Spatial Data by Country.* (2020). Available online at: http://www.diva-gis.org/gdata (accessed April 30, 2020).
32. Ruggles S, Manson SM, Kugler TA, Haynes DA II, Van Riper DC, Bakhtsiyarava M. *IPUMS Terra: Integrated Data on Population and Environment: Version 2 [dataset]*. Minneapolis, MN (2018). Available online at: https://data.terrapop.org/terraclip# (accessed April 30, 2020).
33. Morton DC, Defries RS, Shimabukuro YE. *LBA-ECO LC-22 Land Cover from MODIS Vegetation Indices*. Mato Grosso, Brazil: ORNL DAAC (2013).
34. Solargis. *The World Bank, Source: Global Solar Atlas 2.0, Solar Resource Data: Solargis.* (2019). Available online at: https://solargis.com/maps-and-gis-data/download/brazil (accessed April 30, 2020).
35. RStudio Team. *RStudio: Integrated Development for R*. RStudio, Inc. Boston, MA (2019) Available online at: http://www.rstudio.com/ (accessed July 11, 2019).
36. Mintiens K, Laevens H, Dewulf J, Boelaert F, Verloo D, Koenen F. Risk analysis of the spread of classical swine fever virus through "neighbourhood infections" for different regions in Belgium. *Prev Vet Med.* (2003) 60:27–36. doi: 10.1016/S0167-5877(03)00080-1
37. Postel A, Austermann-Busch S, Petrov A, Moennig V, Becher P. Epidemiology, diagnosis and control of classical swine fever: recent developments and future challenges. *Transbound Emerg Dis.* (2018) 65:248–61. doi: 10.1111/tbed.12676
38. Governo Federal - Brazil. *IBGE - Instituto Brasileiro de Geografia e Estatística.* (2010). Available online at: https://cidades.ibge.gov.br/brasil/mt/panorama (accessed November 30, 2020).
39. Martínez-López B, Ivorra B, Ramos AM, Sánchez-Vizcaíno JM. A novel spatial and stochastic model to evaluate the within- and between-farm transmission of classical swine fever virus. I. General concepts and description of the model. *Vet Microbiol.* (2011) 147:300–9. doi: 10.1016/j.vetmic.2010.07.009

40. de Oliveira LG, Gatto IRH, Mechler-Dreibi ML, Almeida HMS, Sonálio K, Storino GY. Achievements and challenges of classical swine fever eradication in Brazil. *Viruses.* (2020) 12:1–18. doi: 10.3390/v12111327
41. Schettino DN, Abdrakhmanov SK, Beisembayev KK, Korennoy FI, Sultanov AA, Mukhanbetkaliyev YY, et al. Risk for African swine fever introduction into Kazakhstan. *Front Vet Sci.* (2021) 8:1–11. doi: 10.3389/fvets.2021.605910
42. Phillips SJ, Dudík M, Schapire RE. *Maxent Software for Modeling Species Niches and Distributions (Version 3.4.1)*. Available online at: http://biodiversityinformatics.amnh.org/open_source/maxent/ (accessed July 18, 2020).
43. Le CT, Eberly LE. *Eberly*. *Introductory Biostatistics*. 2nd ed. ©2016 Hoboken, NJ: John Wiley & Sons, Inc. (2016). p. 2016.
44. BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. Norma Interna n.05 de 2009. Manual de procedimentos do sistema de vigilância sanitária na zona livre de peste suína clássica. Brasília, DF. Brasil (2009).
45. Herrera-Ibatá DM, Martínez-López B, Quijada D, Burton K, Mur L, Herrera-Ibata DM, et al. Quantitative approach for the risk assessment of African swine fever and classical swine fever introduction into the United States through legal imports of pigs and swine products. *PLoS ONE.* (2017) 12:e0182850. doi: 10.1371/journal.pone.0182850
46. Relun A, Grosbois V, Sánchez-Vizcaíno J, Alexandrov T, Feliziani F, Waret-Szkuta A, et al. Spatial and functional organization of pig trade in different european production systems: implications for disease prevention and control. *Front Vet Sci.* (2016) 3:1–12. doi: 10.3389/fvets.2016.00004
47. Delgado J, Pollard S, Snary E, Black E, Prpich G, Longhurst P. A systems approach to the policy-level risk assessment of exotic animal diseases: network model and application to classical swine fever. *Risk Anal.* (2013) 33:1454–72. doi: 10.1111/j.1539-6924.2012.01934.x

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.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 08 July 2021
doi: 10.3389/fvets.2021.620998

Assessment of Evaluation Tools for Integrated Surveillance of Antimicrobial Use and Resistance Based on Selected Case Studies

Marianne Sandberg[1,2], Ayla Hesp[3,4], Cécile Aenishaenslin[5], Marion Bordier[6], Houda Bennani[7], Ursula Bergwerff[8], Ilias Chantziaras[9,10], Daniele De Meneghi[11], Johanne Ellis-Iversen[2], Maria-Eleni Filippizi[12], Koen Mintiens[13], Liza R. Nielsen[14], Madelaine Norström[15], Laura Tomassone[11], Gerdien van Schaik[8,16] and Lis Alban[1,14]*

[1] Department for Food Safety, Veterinary Issues and Risk Analysis, Danish Agriculture and Food Council, Copenhagen, Denmark, [2] National Food Institute, Technical University of Denmark, Lyngby, Denmark, [3] Department of Bacteriology and Epidemiology, Host Pathogen Interaction and Diagnostics Development, Wageningen Bioveterinary Research, Lelystad, Netherlands, [4] Department of Infectious Diseases and Immunology, Utrecht University, Utrecht, Netherlands, [5] Groupe de recherche en épidémiologie des zoonoses et santé publique, Université de Montréal, Saint-Hyacinthe, QC, Canada, [6] UMR Astre, Cirad, INRAE, University of Montpellier, Montpellier, France, [7] Veterinary Epidemiology, Economics and Public Health Group, Department of Pathobiology and Population Sciences, Royal Veterinary College, London, United Kingdom, [8] Department of Farm Animal Health, Utrecht University, Utrecht, Netherlands, [9] Unit of Animal Science and Unit of Social Science, Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Merelbeke, Belgium, [10] Department of Reproduction, Obstetrics and Herd Health, University of Ghent, Ghent, Belgium, [11] Department of Veterinary Sciences, University of Turin, Turin, Italy, [12] Veterinary Epidemiology Unit, Department of Epidemiology and Public Health, Sciensano, Brussels, Belgium, [13] Food and Agriculture Organization of the United Nations, Rome, Italy, [14] Department of Veterinary and Animal Sciences, University of Copenhagen, Frederiksberg, Denmark, [15] Department of Epidemiology, Norwegian Veterinary Institute, Oslo, Norway, [16] Royal GD Animal Health, Deventer, Netherlands

OPEN ACCESS

Edited by:
Nigel French,
College of Sciences, Massey University, New Zealand

Reviewed by:
Lucie Collineau,
de l'Environnement et du Travail (ANSES), France
Joanna McKenzie,
Massey University, New Zealand

****Correspondence:***
Marianne Sandberg
marsan@food.dtu.dk

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics,
a section of the journal Frontiers in Veterinary Science

Received: *24 October 2020*
Accepted: *21 May 2021*
Published: *08 July 2021*

Citation:
Sandberg M, Hesp A, Aenishaenslin C, Bordier M, Bennani H, Bergwerff U, Chantziaras I, De Meneghi D, Ellis-Iversen J, Filippizi M-E, Mintiens K, Nielsen LR, Norström M, Tomassone L, van Schaik G and Alban L (2021) Assessment of Evaluation Tools for Integrated Surveillance of Antimicrobial Use and Resistance Based on Selected Case Studies. Front. Vet. Sci. 8:620998. doi: 10.3389/fvets.2021.620998

Regular evaluation of integrated surveillance for antimicrobial use (AMU) and resistance (AMR) in animals, humans, and the environment is needed to ensure system effectiveness, but the question is how. In this study, six different evaluation tools were assessed after being applied to AMU and AMR surveillance in eight countries: (1) ATLASS: the Assessment Tool for Laboratories and AMR Surveillance Systems developed by the Food and Agriculture Organization (FAO) of the United Nations, (2) ECoSur: Evaluation of Collaboration for Surveillance tool, (3) ISSEP: Integrated Surveillance System Evaluation Project, (4) NEOH: developed by the EU COST Action "Network for Evaluation of One Health," (5) PMP-AMR: The Progressive Management Pathway tool on AMR developed by the FAO, and (6) SURVTOOLS: developed in the FP7-EU project "RISKSUR." Each tool was scored using (i) 11 pre-defined functional aspects (e.g., workability concerning the need for data, time, and people); (ii) a strengths, weaknesses, opportunities, and threats (SWOT)-like approach of user experiences (e.g., things that I liked or that the tool covered well); and (iii) eight predefined content themes related to scope (e.g., development purpose and collaboration). PMP-AMR, ATLASS, ECoSur, and NEOH are evaluation tools that provide a scoring system to obtain semi-quantitative results, whereas ISSEP and SURVTOOLS will result in a plan for how to conduct evaluation(s). ISSEP, ECoSur, NEOH, and SURVTOOLS allow for in-depth analyses and therefore require more complex data, information, and specific training of evaluator(s). PMP-AMR, ATLASS, and ISSEP were developed specifically for AMR-related activities—only ISSEP included production of a direct measure for "integration" and "impact on decision making." NEOH and ISSEP were perceived as the best tools for evaluation of One Health (OH) aspects, and ECoSur as best for evaluation of the quality of collaboration. PMP-AMR and ATLASS seemed to be the most user-friendly tools, particularly designed for risk managers. ATLASS was the only tool focusing specifically on laboratory activities. Our experience is that adequate resources are needed to perform evaluation(s). In most cases, evaluation would require involvement of several assessors and/or stakeholders, taking from weeks to months to complete. This study can help direct future evaluators of integrated AMU and AMR surveillance toward the most adequate tool for their specific evaluation purpose.

Keywords: integrated surveillance, evaluation, tools, AMR, one health

INTRODUCTION

The importance of combatting antimicrobial resistance (AMR) was highlighted in the Global Action Plan (GAP) released by the World Health Organization (WHO) in 2015 (1). It was further adopted by the Tripartite Collaboration consisting of the members of the WHO, Food and Agriculture Organization of the United Nations (FAO), and the World Organization for Animal Health (OIE) and endorsed by political leaders and the United Nations (UN) General Assembly (2). The Tripartite Collaboration acknowledges that the AMR challenge needs to be addressed using a One Health (OH) approach to reflect that the development and spread of AMR do not respect boundaries between sectors and, therefore, require cross-sectoral collaboration and prevention activities. One of the main objectives of the GAP is to initiate and maintain cost-effective integrated surveillance of antimicrobial use (AMU) and AMR at the global and national levels (1).

Ideally, combatting AMR requires engagement from actors within all sectors of animal health, food safety, environmental protection, plant health, and human health (3). All sectors need to be involved in surveillance to identify emerging resistance, understand the AMR epidemiology, and develop effective policies for AMU and AMR reduction. In short, the integration of sector activities and robust collaboration are essential for successful surveillance and control of AMU and AMR. According to Stärk et al. (4), OH surveillance describes the systematic collection, validation, analysis, interpretation of data, and dissemination of information collected in humans, animals, and the environment to inform decisions for more effective, evidence-based interventions. AMR genes are present in bacteria and spread among humans, animals, and the environment. A program of integrated surveillance of AMR in foodborne bacteria includes coordinated sampling and testing of antimicrobial susceptibility of bacteria from food-producing animals, food, and humans using epidemiological (including sampling) and microbiological methods that enable comparisons of results. The use of comparable methods is necessary to allow comparison of antimicrobial susceptibility results between different areas, countries, and regions (5, 6). Currently integrated OH AMU and AMR surveillance and monitoring systems exist or are under development in many countries (4). However, the surveillance programs do not always address all necessary sectors and they are rarely fully integrated (7). An integrated approach provides a better understanding of the epidemiology of AMR and an easier identification of the best intervention points and enhances the timeliness of surveillance by providing early warning of emergence of new resistant strains from one sector to another. Furthermore, a cross-sectoral collaboration may lead to knowledge/resource sharing, expertise exchange, and capacity building (8), which may result in cost savings and create more efficient and effective systems (9). Full integration might not be necessary to achieve the wanted outputs, and integration and collaboration in itself can be costly without always improving outputs (7, 10). A surveillance approach implies planning, data collection, analysis, interpretation, and dissemination of a given activity. It is useful to apply collaboration across different surveillance activities and integration in all or some of the activities. Identification of the optimal levels of integration to obtain the information needed for decision making is an important task in OH surveillance systems (7, 10).

Aenishaenslin et al. (7) suggested that the value of OH surveillance for AMR can be conceptualized and measured across a selection of different outcomes that can be classified in three dimensions, namely, (i) immediate, (ii) intermediate, or (iii) ultimate. Immediate outcomes include increased understanding of the AMR epidemiology at the human, animal, and environment health interface, and the value would lie in the intellectual or social capital generated. Intermediate outcomes include changes in policy or behaviors, and the expected value is the reduction in AMU and AMR that results from these changes. Ultimate outcomes include tangible benefits such as improved animal, human, and environmental health and associated socioeconomic benefits.

Apart from appropriate planning and designing, surveillance programs also need regular evaluation to remain operational, efficient, and cost-effective. Moreover, evaluation is needed to ensure that the goal is underpinned by the ongoing activities and shared with the essential stakeholders (11). Evaluation is complex and requires agreement on an evaluation objective, a process usually led by food safety/health authorities in consultation with other stakeholders. Secondly, an appropriate evaluation tool should be selected, which requires expertise and knowledge of surveillance evaluation.

Existing tools for evaluation of surveillance [e.g., (12, 13)] are not necessarily appropriate for integrated surveillance as they might not address aspects such as collaboration across sectors (12, 14). Characteristics of OH surveillance programs have been described, and recently, tools to evaluate integrated surveillance systems have emerged, targeting different aspects of the OH or other integrated surveillance activities (7, 11, 15–19). A tool may have been made for evaluation of a particular type of surveillance system, such as animal health surveillance. Still, it might also be used to assess other types of surveillance systems such as AMR surveillance, covering aspects such as sampling strategies and sample sizes of surveillance protocols. The latter may not be covered in details by the tools developed specifically for AMR surveillance evaluation. The different tools vary in their approaches, layouts and user-friendliness, comprehensiveness, terminology, aspects covered, capacity, training, and resources required to use them, as well as their specific usefulness for the evaluation of AMU and AMR surveillance. Hence, a characterization and meta-evaluation of the existing evaluation tools are called for to provide guidance on how to identify the best match between the evaluation objective, the resources available, and the selected evaluation tool.

During 2019–2020, an international network of scientists in the project "Co-Eval-AMR—Convergence in evaluation frameworks for integrated surveillance of AMR" (20) developed guidance for choosing an assessment approach from an inventory of tools suitable for evaluating integrated AMU and AMR surveillance systems, according to the needs of the users. The results presented here originate from the Co-Eval-AMR network aiming to guide assessors in their future selection of evaluation tools. A pilot version of the present study, using one surveillance system case and the first version of the assessment criteria, was published by Nielsen et al. in 2019 (21). The objective of the present study was to describe and assess the characteristics, functionalities, and suitability of tools that might be used for evaluation of integrated AMU and AMR surveillance.

MATERIALS AND METHODS

Overview of the Evaluation Tools

In the following section, the six tools used are presented in brief.

Assessment Tool for Laboratories and AMR Surveillance Systems

The Assessment Tool for Laboratories and AMR Surveillance Systems (ATLASS) is a tool designed by the FAO for assessing and defining targets to improve national AMR surveillance systems in the food and agriculture sectors (18). It is composed of two modules: a surveillance module and a laboratory module. Each module includes two standardized questionnaires, which are to be completed by the assessors. The assessments generate a baseline and classify a "stage" for AMR laboratory capacity detection, AMR surveillance, and dissemination of information.

Evaluation of Collaboration for Surveillance

The Evaluation of Collaboration for Surveillance (ECoSur) tool aims at evaluating the organization, functioning, and functionalities of collaboration taking place in a multi-sectoral surveillance system (11). The final purpose is to assess whether collaboration as planned and implemented is relevant and functional to produce the expected collaborative outputs. The tool relies on the scoring of 22 attributes and three indexes characterizing the organization of collaboration at the governance and operation level and nine attributes referring to core functions of collaboration to ensure the sustainable operation of an effective multi-sectoral surveillance system. Three automatically generated outputs display the evaluation results for attributes and indexes and support the identification of strengths and weaknesses of collaboration and the formulation of recommendations for its amelioration.

Integrated Surveillance System Evaluation Project

The AMR integrated surveillance system evaluation project (ISSEP) tool is a conceptual tool developed in Canada with the aim to structure an evaluation of the added value of integrated surveillance systems for AMR (7). It comprises five evaluation levels that target the evaluation of OH integration in the surveillance system; its capacity to produce integrated information and expertise, to generate actionable knowledge, and to influence decision making; and health and economic impacts. For each level, a set of evaluation questions are defined, and links are made with existing evaluation tools. A semi-quantitative scale is applied to show the level of integration of the surveillance system (19).

Network for Evaluation of One Health

The Network for Evaluation of One Health (NEOH) tool is part of a framework resulting from the EU COST Action "Network for Evaluation of One Health" to provide science-based guidance for the evaluation of One Health and other integrated approaches to health (16, 20, 21). There are four elements, namely, "system definition and description of OH initiative within the system," "theory of change" (ToC), "assessment of OH-ness," and "outcome evaluation." Qualitative assessment as well as semi-quantitative scorings are used for the evaluation of the degree and of the "OH-ness" (OH index and OH ratio) and metrics for different outcomes. Illustrative web diagrams of the distribution of scores for gap identification are presented in the Excel tool for assessment of OH-ness (20).

Progressive Management Pathway Tool for AMR

The Progressive Management Pathway tool for AMR (PMP-AMR) tool is a self-assessment tool designed by the FAO to provide guidance to countries for implementation of their National Action Plans (NAP) for AMU and AMR (17, 21). It includes four focus areas for evaluation: awareness, evidence, governance, and practices. For each focus area, specific activities, achievements, and key performance indicators (KPI) are listed. The tool provides a dashboard, showing the progress made for each focus area toward an optimal and sustainable use of antimicrobials.

TABLE 1 | Overview of eight country-based case studies involving six different tools for evaluation of surveillance of antimicrobial use and resistance, 2019.

Country	Tools	Name of surveillance program	Component(s) covered
Belgium	PMP-AMR and NEOH	Belgian AMR Surveillance Programme (as suggested in the Belgian National Action Plan)	Swine, veal calves, poultry (broilers/laying hens), and humans
Denmark	PMP-AMR, ATLASS, ECoSur, NEOH, and SURVTOOLS	Danish Integrated AMR Surveillance Programme (DANMAP)—selected parts	Pigs
Canada	ISSEP	Canadian Integrated Program for Antimicrobial Resistance Surveillance (CIPARS)	Humans, livestock, and food chain
Italy	NEOH, PMP-AMR, and SURVTOOLS	Italian ClassyFarm Surveillance Programme (data from the Piedmont region)	Pigs
Norway	PMP-AMR and NEOH	NORM-VET monitoring program for antimicrobial resistance in the veterinary and food production sectors (NORM-vet)	Broilers
The Netherlands	SURVTOOLS and NEOH	Monitoring of Antimicrobial Resistance and Antibiotic Usage in Animals in the Netherlands (MARAN)	Broilers, slaughter pigs, veal calves, and dairy cows
United Kingdom	ISSEP	Surveillance of AMU and AMR in the United Kingdom	Humans, livestock, and food chain
Vietnam	ECoSur	Surveillance of AMR in Vietnam	Humans, food products, and animals

ATLASS, the Assessment Tool for Laboratories and AMR Surveillance Systems; ECoSur, Evaluation of Collaboration for Surveillance tool; ISSEP, integrated surveillance system evaluation project; NEOH, Network for Evaluation of One Health; PMP-AMR, The Progressive Management Pathway tool on AMR; AMU, antimicrobial use; AMR, antimicrobial resistance.

Survtools

SURVTOOLS was developed as a part of the EU FP7-funded project RISKSUR: risk-based animal health surveillance systems. The evaluation tool (EVA tool) is a support tool for the evaluation of animal health surveillance systems, developed to provide guidance for evaluation of animal health surveillance including economic evaluation (12, 21). When planning an evaluation, the user is guided through three main steps: defining the evaluation context; defining the evaluation question; and selecting the evaluation attributes and the economic criteria. Furthermore, the tool provides additional information and guidance on how to use the evaluation plan to perform the evaluation and how to report on the evaluation outputs. An online web version of the EVA tool is available (12).

Methodology Used to Assess the Tools

The details of the scoring scheme for functional aspects, the SWOT-like approach, and the scoring scheme for the themes describing the scope of the tools are presented below.

The Case Study Approach

A total of eight country-based case studies of AMU and AMR surveillance systems were included in the study (**Table 1**). Each country-based case study was undertaken by individuals or a group of individuals with expertise on the respective national cases (hereafter called the assessors), making a total of 20 assessors. The choice of case was the NAP on AMR or parts of it in the respective assessor's country. To collect the information needed to carry out the assessment, the assessors reached out to additional experts and other sources.

The assessors met regularly, and initially, there was an assessment methodology developed in collaboration with selected members of the Co-Eval-AMR network group. The methodology included two standardized scoring schemes; a strengths, weaknesses, opportunities, and threats (SWOT)-like analysis scheme; and templates for reporting and instructions. The evaluation tools were applied on the country-based case studies using one or more tools on each case. Overall, the outcome was the users' experience regarding applicability of the tool. Each tool was assessed between one and four times.

Scoring Functional Aspects

A scoring scheme aiming at assessing 11 functional aspects was developed, and answers were scored numerically, where 1 = not covered, 2 = not well-covered, 3 = more or less covered, and 4 = well-covered. With each score, a comment was requested explaining the score. The 11 aspects were as follows: (1) user friendliness, (2) compliance with evaluation objectives, (3) efficiency (number of people and time taken vs. what the evaluation should be used for), (4) use of a step-wise approach to the evaluation, (5) overall appearance, (6) generation of actionable evaluation outputs, (7) evaluation of OH aspects, (8) workability in terms of required data, (9) workability in terms of required people to include, (10) workability in terms of analysis to be done, and (11) time taken for application of the tool.

The combined scores for each tool were presented in a heat map. In the case one assessor/assessor group scored over a range of numbers, averaging was used followed by rounding up if necessary to obtain a whole number for the total score. A crude summary score for each tool was calculated and presented in heat maps. The scores should only be interpreted relatively within this study material. The justification for each score, provided by the individual assessors, was condensed by the first author and checked for correctness by the other authors, and the "condensed results" were then presented.

A SWOT-Like Approach

A SWOT-like scheme was developed asking the assessors to answer four questions: (1) things that I liked or that the tool covered well; (2) things that I struggled with when using this tool; (3) things people should be aware of when using this tool; and (4) things that this tool covers insufficiently. A qualitative synthesis of the result was done in two steps. First, all individual phrases were captured. In a second step, phrases with the similar meaning were reduced into one, implying that a phrase was simplified or made into one word, if possible. It also implied that no phrase or word was repeated for each of the SWOT analyses and tools. The first synthesis was carried out by the assessors for the tools they had applied. The second synthesis was condensed by two of the authors, and the condensed results were checked for correctness by the other authors and subsequently presented.

Scoring Themes for the Scopes

A second scoring scheme consisted of eight themes to describe the scope of the tool: developed specifically for AMU and AMR, collaboration, resources, output and use of information, integration, governance, adaptivity, and technical operations. Seven of the themes included in the scheme were developed in the Co-Eval-AMR project (22). Additionally in this study, the theme governance was added. The objective was to score how well each theme was covered by the specific evaluation tool. A more detailed description of the individual theme scope is given in **Table 2**. The same scoring scale as in the Scoring Functional Aspects section was used. The combined scores for each tool were presented in a heat map, based on a similar way of estimation as described in the Scoring Functional Aspects section. A crude summary score for each tool was calculated, but this should only be interpreted relatively within this study material. Again, the free text justifications behind the scores provided by the assessors were synthesized by the first author, checked for correctness by the other authors, and subsequently presented.

TABLE 2 | Description of the themes describing the scope of the tool in relation to surveillance identified in the Co-Eval-AMR project and used for the additional assessment of the evaluation tools for surveillance programs/activities.

Theme	Description of the themes
AMU and AMR	Questions that are specifically addressing the case of AMR (occurrence, prevention, or response) or AMU (recording and management)
Collaboration	Questions on the framework of collaboration (organization of roles and responsibilities) and the object of collaboration (exchange of data, information, and knowledge and sharing of capacities). This category also covers questions about the inclusive participation of stakeholders (e.g., considering gender)
Resources	Questions quantitatively addressing human, physical, and financial resources. Questions on the training level of human resources are also considered in this category
Output and use of information	Questions on surveillance outputs that are provided to inform public and private stakeholders, their use to inform decision making, and the benefits from this use (expected, perceived, or measured)
Integration	Questions considering three levels of integration: • integration of data systems (within organizations and at national, regional, or international level; data systems interoperation; and adherence to international testing and data standards) • integration between sectors and disciplines (knowledge integration, shared decision making and planning, and formulation of common goals) • integration in the national and international context motivating the need for surveillance (link to decision making, shared decision making, and planning between countries)
Governance*	Questions related to the legislative framework as well as the steering and coordinating mechanisms for the surveillance system: legislation, steering, and criteria (limits and goals for reduction)
Adaptivity	Questions on any structural elements allowing for the surveillance system to adapt and evolve. This may include not only tools, plans, and agreements to evolve (e.g., continuous learning programs and external evaluation) but also the features of management and governance allowing for regular evaluation and adaptation of operations (e.g., frequency of meeting and regularity of progress reports)
Technical operations	Questions on technical features of surveillance operations (surveillance design, laboratory capacities, management of specimens, tests applied, data management, and analysis), their quality management (SOP, traceability), and the assessment of their performance (sensitivity and specificity)

**Governance was included as a separate theme in this study but is not a separate theme on the https://guidance.fp7-risksur.eu/welcome/decision-support/.*

RESULTS

All detailed answers and justifications from the scoring of the functional aspects and the themes and from using the SWOT-like approach are published on the Co-Eval-AMR project webpage (https://coevalamr.fp7-risksur.eu/) and in Nielsen et al. (21).

Scoring of the Functional Aspects of the Tool

The results from the scoring of the case studies according to the 11 functional aspects of AMU and AMR surveillance systems are shown in **Table 3**. A summary of the justifications behind the scores is shown in **Table 4**. A crude summary of the scores showed that ISSEP and NEOH had the lowest scores, 25 and 30 respectively of the total 44 that could have been achieved. ATLASS and PMP-AMR had the highest, 39 of the 44 possible.

For OH aspects, ATLASS and NEOH scored the highest. PMP-AMR, ATLASS, ECoSur, and NEOH provide semi-quantitative scores for the aspects evaluated, whereas ISSEP and SURVTOOLS will result in a plan for how to conduct evaluation(s). ISSEP, ECoSur, NEOH, and SURVTOOLS allow for in-depth analyses and, therefore, require more complex data, information, and specific training of the evaluator(s). PMP-AMR and ATLASS seemed to be the most user-friendly tools, particularly designed for food safety authorities managing the surveillance system.

The SWOT-Like Approach

The results of the SWOT-like approach applied to assess the tools are shown in **Table 5**. The variation in answers to the four SWOT-like questions was low among the assessors of each tool, indicating consistency regarding the general impression of the tools. The PMP-AMR and ATLASS were liked for the semi-quantitative scorings that could be made directly and that the tools were particularly made for evaluation of AMR

TABLE 3 | Result of the scoring of all six tools with respect to the 11 functional aspects, shown as a heat map (the number of times the tool was assessed is given in the bracket). The scoring scale used was where 1 (red) = not covered, 2 = not well covered (orange), 3 = more or less covered (yellow), 4 = well covered (green).

	ISSEP (2)	ECoSur (2)	ATLASS (1)	PMP–AMR (4)	NEOH (5)	SURVTOOLS (2)
User friendliness	2	3	4	4	2	4
Meets evaluation needs/requirements	3	4	2	3	4	3
Efficiency	2	4	4	4	3	3
Use of a step-wise approach to the evaluation*	3	2	4	4	3	2
Overall appearance**	2	3	4	4	2	4
Generation of actionable evaluation outputs	2	4	4	4	3	2
Allows evaluation of one health aspects	3	3	4	2	4	2
Workability in terms of required data (1: very complex and 4: simple)	2	3	1	4	2	3
Workability in terms of people to include (1: many and 4: few)	2	3	4	3	2	4
Workability in terms of analysis to be done (1: difficult and 4: simple)	2	4	4	4	3	3
Time taken for application of tool: time (1: >2 months, 2: 1–2 months, 3: 1 week–1 month, and 4: <1 week)	2	3	4	3	2	3
Crude summary score	25	36	39	39	30	33

*Only scored by 11 of the 20 of the assessors. **Only scored by one of the two assessors of ISSEP. The scoring scale used was as follows: 1 = not covered (red), 2 = not well-covered (orange), 3 = more or less covered (yellow), and 4 = well-covered (green).*

surveillance systems. What is not covered in these two tools is the environmental, plant, and human parts of surveillance.

The ECoSur was liked because it allowed evaluation of collaboration in detail; however, the level of abstraction in the language in the existing version of the tool was a struggle. ISSEP was liked because it described the relationship between the integrated surveillance activities for AMU and AMR, OH outputs produced, and the different expected outcomes very well.

NEOH was liked for being comprehensive, multi-faceted, and fit for a transversal analysis of OH initiatives. The main struggle related to NEOH was that it was cumbersome and time-consuming to use. Similarly, SURVTOOLS was liked because information for evaluation of all aspects of a surveillance system including the epidemiological part is provided as scientific references. Furthermore, an epidemiological calculator is provided. However, SURVTOOLS is one of the tools that only provide an evaluation plan.

Scoring of the Themes Describing the Scope of the Tool

The results from the scoring of each tool for the eight themes describing the scope of the tool in relation to surveillance are shown in **Table 6**. A summary of the justifications behind the scores are shown in **Table 7**. A crude summary of the scores for the tools, regarding which themes they covered, showed a limited variation. ATLASS had the highest crude summary scores of 28 followed by ISSEP and ECoSur both with 25.

PMP-AMR, ATLASS, and ISSEP have been developed specifically for AMR-related activities. NEOH and ISSEP were perceived as the best tools for evaluation of all OH aspects, and ECoSur and ISSEP for evaluation of the quality of collaboration. ATLASS is the only tool evaluating laboratory activities specifically. Only ISSEP produced a direct measure of the "integration" and "impact on decision making." SURVTOOLS has an epi-sample size calculator and is, hence, the only tool providing a quantitative assessment of the technical operations in surveillance.

DISCUSSION

Tools Developed Specifically for Evaluating AMU and AMR Surveillance

Only PMP-AMR, ATLASS, and ISSEP have been developed especially for evaluating AMU and AMR surveillance. Generally speaking, ISSEP was the only tool assessed that addressed AMU and integration aspects. The strengths of PMP-AMR and ATLASS are governance and, hence, strategic implementation of NAPs. PMP-AMR addresses neither evaluation of design of surveillance nor integration or collaboration. ATLASS is structured in such a way that detailed information about the sectors involved and the laboratories in the surveillance system can be captured. Thereby, it addresses the gaps in a laboratory's capacity to implement surveillance activities. A quantitative evaluation of the epidemiological designs is impossible in ATLASS. Moreover, ATLASS does not provide an output of the level of integration—but all data collated could provide the evaluator with an impression of the level of integration in the system evaluated.

However, the other evaluation tools were also considered suitable for evaluation of AMU and AMR surveillance programs. In fact, several of the tools showed a high degree of flexibility and were applicable to different surveillance evaluation objectives. Still, the most accurate evaluations

TABLE 4 | Results of synthesis of the underlying reasoning for the scoring according to the 11 functional aspects.

	ISSEP (CA and UK)	ECoSur (VN and DK)	ATLASS (DK)	PMP-AMR (BE, DK, IT, and NO)	NEOH (DK, BE, IT, NO, and NL)	SURVTOOLS (DK and NL)
User friendliness	Conceptual framework easy to follow. Evaluation(s) more complicated	Relatively easy to understand and could be improved with a web interface	Can be used without much preparation	Easy to understand and fill in without training	Complex without training, long/exhausting. Scoring OH attributes is relatively simple	Tool itself is easy to fill in, but more complex to conduct evaluations
Meets evaluation needs/requirement	Relationships of integrated surveillance activities/outputs described. No guidance on evaluation	Measurement of the level of collaboration, but not the overall added value of collaborating for surveillance activities	Predefined network is comprehensive, but measurement of smaller progressions not possible	Qualitative scoring system could be improved. Partially meeting needs for AMU and AMR evaluation(s)	Comprehensive, less intuitive to use for specific technical details/laboratory part	Epidemiological performance easiest to perform, other parts more difficult
Efficiency	Requires a lot of time to conduct evaluation(s)	Evaluation matrix easy to understand/apply. Validation meeting with stakeholder required	Questionable whether all data are really needed	Easy to fill in. Immediate generation of results. Suitable for administrators	Takes a long time to fill in tool. "Theory of change" (ToC) could be better integrated. Not a management tool	Takes some time to fill in the tool and longer time for evaluations
Use of a step-wise approach to the evaluation	The tool has five evaluation levels	Only possible to follow progress of collaboration if evaluation repeatedly done	Follows a step-wise approach with areas containing sub-categories reflecting the level of implementation and geography	Follows (inherent) a step-wise approach with four levels with logic progression. Level 1: planning of activity/locally and levels 2, 3, and 4: undertaking activities /regionally/nationally	Stepwise approach to evaluation with the following steps: context description, initiative within context description, OH-ness, and ToC (outcome and impact). If evaluation of progress, repeated evaluations over time needed	Does not follow a step-wise approach. Order would be given by choice of evaluation question(s) and not by the toll itself
Overall appearance	The conceptual framework is well-presented	Well-structured, web platform needed	Useful for evaluation of AMU and AMR and residue surveillance at laboratory level	The general assessment part excellent, the sector specific less so. Nice layout, some parts could be improved	Extensive handbook. Excel tool is mostly understandable but too compressed in layout	Generates evaluation plan. Takes time to evaluate integrated surveillance. Objective results
Actionable evaluation outputs	No clearly defined actionable outputs	Generation of three graphical outputs of results: one for organizational attributes, one for organizational indexes, and one for functional attributes	Monitors progress and suggests next level	Actions can be agreed upon during assessment. Graphics could be improved. Gaps in sector evaluation	A web diagram makes it easy to identify gaps. Scoring is subjective: may lead to biased results	Not generated by tool. Evaluation could generate first-level actionable outputs (e.g., effect of designs). Other outputs on, e.g., awareness more difficult to obtain
Evaluation of OH aspects	Comprehensive	Existence of specific attributes measuring OH aspects, e.g., shared leadership	All sectors covered and measures integration	Not addressed in particular	Major strength of the system's approach and the tool	Can be used for all aspects. Layout does not support all components
Workability regarding required data (1: very complex and 4: simple)	Large amounts of data required	Dependent on the complexity of the surveillance system evaluated	Large amounts of data required	Apparently simple. Data are easily accessible	Requires effort/time to gather data. Some data complex to get (e.g., learning/system organization)	Relatively simple to get the data for filling in tool, but for some evaluation questions/objectives, it is complex to acquire the data

(Continued)

TABLE 4 | Continued

	ISSEP (CA and UK)	ECoSur (VN and DK)	ATLASS (DK)	PMP-AMR (BE, DK, IT, and NO)	NEOH (DK, BE, IT, NO, and NL)	SURVTOOLS (DK and NL)
Workability regarding required people (1: many and 4: few)	Stakeholders from all sectors required	Meant to be applied by an evaluation team	Needs expertise from several areas	All stakeholders invited to evaluation meetings (2 days). One person can do evaluation, but then data capture needed (e.g., through interviews)	Interview of essential actors and stakeholders, but only one evaluator needed	Few people needed
Workability regarding analysis to be done (1: difficult and 4: simple)	No guidance on analysis provided	Easy identification of the criteria influencing the evaluation results to support formulation of recommendations	Automated analysis	Generated by the tool. Mostly yes/no answers to questions	Once tool is filled in, it provides support for analyses. Comparing ToC and scoring difficult	Dependent on the number and complexity of evaluation question(s)
Time (1: >2 months, 2: 1–2 months, 3: 1 week–1 month, and 4: <1 week)	Long time required for evaluation(s)	Dependent on the complexity of the surveillance system evaluated	If assessor experienced in surveillance or detailed NAP report available, takes relatively short time	Take relatively short time	Filling in the Excel tool is relatively fast once you have the information ready. Defining the ToC and gathering data is time-consuming	Short time to fill in tool. Long time for some of the evaluation objectives/questions

originated from the tools that match the specific evaluation questions. Generally speaking, an evaluation of integrated AMU and AMR surveillance systems will benefit from using tools developed specifically for evaluating AMR surveillance and OH aspects since specific characteristics are encountered.

User Friendliness and Potential Value

The PMP-AMR and ATLASS tools are to a high extent self-instructive and the questions were, therefore, easy to answer. The structure of PMP-AMR was very easy to understand, whereas ATLASS was more complicated to fill in, since it comprises many questions at all levels of organization. The handbook/guidance/surveillance evaluation wiki to SURVTOOLS was perceived by some of the assessors as very clear and easy to read. It also provides advice on how to cover many of the required aspects of evaluation. The online evaluation tool itself looks very aesthetic but covers less information than the handbook and is not fully self-instructive for all evaluation objectives. NEOH requires knowledge of both the relevant context (in the NEOH framework denoted "the underlying system and its system boundaries") and the integrated surveillance activities ("the initiative under evaluation") in question, because the assessor must define all components that form part of the underlying system (the context) included in or affected by the surveillance. NEOH allows the assessor to identify and assess expected outcomes based on the ToC of the initiative. ToC is a specific type of methodology for planning, participation, and evaluation that is used in companies, philanthropy, and not-for-profit and government sectors to promote social change. Further, it defines long-term goals and then maps backward in time to identify the necessary preconditions and actions to be taken. The ToC focus will lead to learning and perhaps a better understanding of the surveillance and its potential societal impacts. It is easy to get lost in the extensive handbook published to assist in using NEOH, and a quick guide is currently missing. The many detailed questions about integration such as OH implementation including systemic organization and level of sharing (infrastructure aspects) and learning (operational aspects) allow for nuances in the answers and, thereby, a better quality of the results. However, the evaluator should be aware that applying this tool requires time investment and training, including specific training in "systems thinking."

ISSEP, ECoSur, and SURVTOOLS also allow for an in-depth analysis requiring collection of more complex data and information. For SURVTOOLS, a specific training in design of epidemiological studies and a wide spectrum of analytical methods are needed before a full exploitation of the tool can be expected. Many of the tools could also be used to guide the design of AMU and AMR surveillance systems in addition to evaluation of existing systems.

Many of the tools, especially ATLASS, produce intermediate outputs of how well the different parts of the program are integrated and how well the partners collaborate. In contrast, the interpretation of evaluation results of ECoSur supports the identification of strengths and weaknesses of collaboration

TABLE 5 | Synthesis of phrases provided in the SWOT analysis of six different evaluation tools used in eight country-based case studies.

	ISSEP (CA and UK)	ECoSur (VN and DK)	ATLASS (DK)	PMP-AMR (BE, DK, IT, and NO)	NEOH (DK, BE, IT NO, and NL)	SURVTOOLS (DK and NL)
Like	Provision of a conceptual model for integrated surveillance of AMU and AMR surveillance	Comprehensive evaluation of collaboration Participatory evaluation Provision of a clear guidance	Automated analyses Progress monitoring Easy to communicate results	Easy progress monitoring Participatory evaluation Evaluation of the implementation levels	Comprehensive and multi-faceted OH assessment Evaluation of implementation quality	Objectivity Comprehensive framework for different evaluation aspects
Difficulty	No provision of guidance to collect and analyze of data	Evaluation of collaboration only	Why need for such detailed data?	Subjectivity Crude scoring method	Cumbersome	Requirement of training for conducting evaluation Time-consuming for evaluation of complex aspects
Be aware of	Necessary combination with other tools depending on the evaluation question	Characterization and evaluation of integration regarding collaborative objectives and context	Not possible to measure minor progress of epidemiological performance	Complexity in terms of people to include Self-assessment tool Results not comparable across countries	Requirement of training for application Resource demanding	Provision of an evaluation plan only, not AMU and AMR specific
Not covering	Guidance for conducting evaluation	Surveillance performance	Environment and plant sector specifically	One Health assessment Distinction between ongoing and incomplete activities Evaluation of quality of activities	Progress monitoring Surveillance performance	Laboratory aspects One Health assessment

TABLE 6 | Results of scoring of six tools for AMR surveillance evaluation according to eight themes describing the scope of the evaluation tool (the number of times the tool was assessed is given in the bracket).

	ISSEP (2)	ECoSur (2)	ATLASS (1)	PMP-AMR (4)	NEOH (5)	SURVTOOLS (2)
AMU and AMR specific	4	2	4	4	3	2
Collaboration	4	4	4	2	4	2
Resources	2	4	3	3	3	3
Output and use of information	4	3	3	3	3	2
Integration	4	4	3	2	4	2
Governance*	3	2	4	4	1	2
Adaptivity	2	4	4	4	3	2
Technical operations	2	2	3	2	2	2
Crude summary score	25	25	28	24	23	17

**Governance was included in this study by 9 of the 20 of the assessors (however, not a separate theme on the https://guidance.fp7-risksur.eu/welcome/decision-support/). The scoring scale used was 1 = not covered (red), 2 = not well-covered (orange), 3 = more or less covered (yellow), and 4 = well-covered (green).*

and the formulation of recommendations. Among the six tools investigated, this tool allows for addressing collaboration in most detail and in different dimensions.

It became clear during this study that adequate resources are needed to perform a full evaluation, sometimes requiring involvement of many assessors and/or stakeholders, and it might take weeks to months to finalize. For all tools, training and instructions would be required to understand the tools sufficiently well to work effectively. Furthermore, the assessor should preferably have a moderate level of understanding of surveillance processes. Moreover, it is important to balance the degree of complexity of the evaluation tool with the available resources in terms of number of people, data, and time.

Output and Use of Information (Impact)

The ISSEP and partly SURVTOOLS approaches provide a conceptual basis for structuring the evaluation of different surveillance outcomes, from the level of integration to the evaluation of the decisions as well as economic efficiency. The outputs of an evaluation may consist of first-level outputs, such as epidemiological performance measures, as well as intermediate outputs, such as how well the system is integrated. For successful AMU and AMR surveillance, the final impact would be that there are antibiotics available to treat future generations of humans and animals against infections. PMP-AMR and ATLASS only produce intermediate outputs through the theme collaboration. It remains unknown whether this and similar themes really reflect what is necessary to implement to reach the final desired impact

TABLE 7 | Synthesis of the underlying reasoning for the scoring according to the eight themes describing the scope of six AMR surveillance evaluation tools.

Themes	ISSEP (CA and UK)	ECoSur (DK and VN)	ATLASS (DK)	PMP (BE, DK, IT, and NO)	NEOH (DK, BE, IT, and NO)	SURVTOOLS (DK and NL)
AMU and AMR	Framework developed specifically for AMU and AMR	Not specific for AMU and AMR but can be easily applied for AMU and AMR	Designed for AMU and AMR and residues	Designed for AMU and AMR. Misses components besides farm animals	Not designed for this purpose but can be adapted (e.g., under "objectives of the initiatives"). Most, if not all, of these questions are expected to be included as part of elements 2 and 3	Not developed for AMU and AMR
Collaboration	Allows evaluation of collaboration between the different organizations involved	Collaboration at the heart of the tool, e.g., cross sectors/professions/disciplines/public/private organizations/geographical/governance/implementation	Between sectors, all actors, and all levels	Reporting, not data exchange. Participation stakeholders/actors considered for institutions. Gender not considered. Promotes knowledge sharing	Collaboration included in all aspects (in element 1).	No particular guidance; difficult to understand how to evaluate the amount of collaboration
Resources	Questions not included, but data can be collected if economic analysis is part of evaluation	Financial aspects addressed in detail at different levels: planning, allocation, and use	Ask for unlimited or limited budget	Only present in "governance"	Only covered in "planning" and "sharing" aspects of OH-ness evaluation. Focus on allocation: resources to achieve objectives of the initiative (human/physical/financial resources and training). In NEOH handbook, chapter about economic evaluation of OH	Generates a framework for economical evaluation. Epi-calculator available
Output and use of information	Allows to evaluate the outputs of integration and the impacts of integration on decision making and on health and economic outcomes	Allows conclusion about appropriateness of collaborative activities for the expected collaborative outputs (e.g., improving the epidemiological performance). No quantification of impacts on the surveillance value and of costs.	Intermediate-level outputs best addressed	Outputs evaluated (better than impacts), e.g., production of guidelines on prudent use of AM, data reporting to organizations. Not covered in "awareness"	Reveals gaps in OH and where impact of the initiative being evaluated might be improved. Outcomes/impacts depend on type of OH initiative and boundaries of the contextual "system" and resulting ToC. Hence, the evaluator must take into account the appropriate parameters (data and disciplinary paradigms)	If full evaluation, most of the aspects would be covered and impact/output might be possible to measure. Unclear how to measure for intermediate outputs/impacts
Integration	Allows evaluating impacts of integration on decision making/health /economic outcomes	Assessment of the organization and functions of collaboration to achieve the desired level of integration, in coherence with the context	Addressed for many areas, not in-depth	Questions on data reporting, adherence to international testing/data standards/level of knowledge/shared decision making. Not across sectors	Integration measures on many levels, e.g., data integration in organizations, national, regional, or international level, and systems interoperation between different sectors. International testing/data standards not included, unless it is included in "initiative" being evaluated	Not included or advanced to evaluate
Governance	Partly considered when looking at the overall organization/management	Inclusion of many aspects: rationale and objective of collaboration, responsibilities of stakeholders, functionality of governance mechanisms, etc.	Addressed for many areas	Well covered, one main focus of the tool	Partially in the thinking and systemic organization of the OH-ness evaluation. The tool includes consideration of legislation and National Action Plan, if nation is identified as dimensions in the "system"	Not included, but some aspects might be covered if conducting process evaluation

(Continued)

TABLE 7 | Continued

Themes	ISSEP (CA and UK)	ECoSur (DK and VN)	ATLASS (DK)	PMP (BE, DK, IT, and NO)	NEOH (DK, BE, IT, and NO)	SURVTOOLS (DK and NL)
Adaptivity	The tool does not cover this aspect	No monitoring of the progress of collaboration. Monitoring and evaluation of collaboration performance	Measure progress	Designed for measuring improvement	Can be assessed through repeated evaluations. If a dedicated process evaluation is done, the progress can be studied. Evaluator and framework design are “key”	Obtainable if evaluation is done twice (over time) to identify improvement
Technical operations	Includes questions on technical aspects, e.g., sampling/methodology	No evaluation of surveillance performance, even if taken into account evaluation of certain collaboration attributes	Quality of epidemiological designs not covered	Includes questions on the targets of surveillance (e.g., pathogens). Low without ATLASS	Not among evaluation objectives. Include few questions probing for capacities/data handling. Could be part of operations assessment of OH-ness, but extent lies upon evaluator and framework followed	Cover technical efficiency/performance, other laboratory aspects not guided/covered

in the AMU and AMR surveillance. ATLASS and PMP-AMR are contributing to this final impact by providing evaluation of the governance, strategic support, and budgets for surveillance. An evaluation of the impact of surveillance will be further addressed in a phase 2 of the Co-Eval-AMR, just initiated as a follow-up project funded by Joint Programming Initiative for AMR (JPIAMR) (https://www.jpiamr.eu/project/coeval-amr-phase-2/).

The Limitations of the Study

We have presented the experiences of eight country-based case study groups in using six evaluation tools. Due to resource constraints, some tools were only assessed in a limited number of case studies. Some of the tools were only scored by two assessors, by two assessor groups, or by the creator(s) of the tool. For NEOH, ECoSur, ISSEP, and PMP-AMR, co-developers of the tools were involved in the assessment, but the tools were also assessed by other case study groups. The assessments were done by different persons, and the scores were perceived as crude and subjective. The assessors had varying levels of understanding of the evaluation tools; some were involved in the development of one of the tools, whereas others were trained in using a specific tool. The first group of assessors may have had greater insights into the tool(s) that they assessed and may have been biased in some aspects of the assessment, e.g., user friendliness. During the assessment process, there was some convergence in the scoring done by the assessors due to the development of a common understanding of the words and sentences used in the tools. Therefore, the results of the scoring of the functional criteria had a higher variation than the results of the scoring of the attributes that was done later in the process. The qualitative assessments are probably more informative for the pros and cons of each tool than the actual scores. The remaining tools were assessed by “non-developers.”

Monitoring and stewardship of AMU as part of AMR surveillance were not addressed in the assessment. In the second phase of the Co-Eval-AMR, additional assessments using other tools are planned. Moreover, focus will be on how to assess the impact of integrated surveillance systems for AMU and AMR as well as on how to evaluate governance. The online assessment system made by the Co-Eval-AMR project group can also be used by other scientists for doing similar comparisons and hence more experiences will be collected (https://coevalamr.fp7-risksur.eu/). Most of the participants in the case study groups were veterinarians or professionals working within veterinary public health. Persons in human health only participated indirectly when being interviewed, and there was no focus on the environment. In phase 2 of the project, collaboration among others and with social scientists will broaden the scope and the way of looking at surveillance and evaluations.

Development of Assessment Methodology and Reporting the Results to Capture the Variation in the Underlying Reasoning

In the Co-Eval-AMR project, the methodology was developed to capture the usability of the tools for evaluation of AMU and

AMR surveillance activities in a systematic way, allowing for comparisons between assessors. The assessment methodologies covered aspects known as contributing to controlling AMR, e.g., evaluation of OH aspects, mentioned by for instance Holmes et al. (3). The 11 functional aspects included elements such as user-friendliness and whether the tool meets evaluation needs/produces actionable outputs and the resource needed related to data, manpower, and time. In the second phase of the Co-Eval-AMR project, improvements in assessment criteria will be considered.

As opposed to the other tools, ISSEP and SURVTOOLS generated only a plan for how to conduct the actual evaluation based on the chosen evaluation questions. Hence, scoring these for some of the 11 functional aspects and the eight themes was difficult. The PMP-AMR, ATLASS, ECoSur, and NEOH tools provide semi-quantitative evaluation outputs. PMP-AMR and ATLASS measure the progress over time and can be used repeatedly. Moreover, PMP-AMR and ATLASS seemed suitable for non-scientists too, since they do not require specific knowledge of epidemiology and surveillance for their application. The tools are not interchangeable—they do not have common scopes and objectives; therefore, one cannot choose a tool only based on the appreciation as assessed only by these case studies. Some lack of consistency exists between the work done in the different working groups of the Co-Eval-AMR project, because some of the development of methodologies was undertaken simultaneously in all working groups, e.g., governance was therefore only assessed by "country case study groups" with a few exceptions. The latter reflected in the missing data given as a footnote in **Table 3**.

Establishing a Data Capture System for Generation of Assessment Experiences

The developed reporting template enables other assessors to report their experiences using the tools in a comparable way. The template consists of four sections; (1) general information, (2) scoring of 10 functional aspects, (3) SWOT-like approach, and (4) scoring of eight themes describing the scope of the tool. The idea was to develop a kind of user experience scoring overview similar to many internet applications such as TripAdvisor and Google reviews providing the readers with quick, yet detailed, insights of the tools. The template is placed in an online platform on the homepage of Co-Eval-AMR (https://coevalamr.fp7-risksur.eu/). We encourage users of the tools to provide their inputs and expect that over time a growing collection of experiences will help users in choosing more easily among the existing tools.

CONCLUSION

Evaluation of integrated surveillance is needed at regular intervals using robust tools. It is important to choose a tool that adequately addresses the specific evaluation objectives. We provided a portfolio of the experiences of 20 users representing eight country-based case studies in which six different tools were applied, to highlight their attributes, pros and cons, and requirements.

Only PMP-AMR, ATLASS, and ISSEP have been developed especially for evaluating AMU and AMR surveillance—with ISSEP being the only tool providing a semi-quantitative score of AMU and AMR integration. All six tools demonstrate a high degree of complementarity. Depending on the evaluation questions selected, assessors may choose among the different tools to conduct the evaluation as such, namely, ECoSur for addressing collaboration, NEOH for the OH-ness and the relationship between ToC and expected outcomes of the surveillance, ATLASS for the laboratory capacities, and SURVTOOL for epidemiological and economic performance.

An online platform for reporting of users' experiences will help users interested in conducting an evaluation of AMU and AMR surveillance in choosing the most adequate tools for their specific evaluation needs: https://guidance.fp7-risksur.eu/welcome/decision-support/. Furthermore, this platform could help further extend general user experience of AMU and AMR surveillance evaluation tools.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

MS, AH, MB, and LA were substantially involved, and took the lead, in all steps of the study from the conception to the design of the work. AH and UB designed the layout of **Table 3** and **Table 6**. All authors contributed to the assessments and/or to the interpretation of the results of these. Most of the authors initially drafted parts of the paper. All authors approved the final version of the paper. They also agreed to be accountable for all aspects of the work, in ensuring that questions related to the accuracy or integrity of any part of the work were appropriately investigated and resolved.

FUNDING

Co-Eval-AMR was funded by JPIAMR (www.jpiamr.eu) and led by Dr. Barbara Häsler from grant holder Royal Veterinary College in the UK, receiving funding from the Medical Research Council, grant number MR/S037721/1.

ACKNOWLEDGMENTS

We thank all participants of Co-Eval-AMR network project for their contribution as well as the stakeholders in the different case studies, who provided us with information to perform the assessments.

REFERENCES

1. World Health Organization. *Global Action Plan on Antimicrobial Resistance.* WHO Press (2015) p. 1–28. Available online at: http://www.who.int/drugresistance/global_action_plan/en/ (accessed October 1, 2020).
2. WHO/FAO/OIE Report. *Monitoring and Evaluation of the Global Action Plan on Antimicrobial Resistance: Framework and Recommended Indicators.* (2019). Available online at: https://www.oie.int/fileadmin/Home/eng/Media_Center/docs/pdf/PortailAMR/EN_MandE_GAP_AMR.pdf (accessed October 1, 2020).
3. Holmes AH, Moore LS, Sundsfjord A, Steinbakk M, Regmi S, Karkey A, et al. Understanding the mechanisms and drivers of antimicrobial resistance. *Lancet.* (2016) 387:176–87. doi: 10.1016/S0140-6736(15)00473-0
4. Stärk KDC, Arroyo Kuribreña M, Dauphin G, Vokaty S, Ward MP, Wieland B. One health surveillance - more than a buzz word? *Prev Vet Med.* (2015) 120:124–30. doi: 10.1016/j.prevetmed.2015.01.019
5. World Health Organization report 2017. *Integrated Surveillance of Antimicrobial Resistance in Foodborne Bacteria: Application of a One Health Approach.* Available online at: https://apps.who.int/iris/bitstream/handle/10665/255747/9789241512411-eng.pdf?sequence=1 (accessed March 1, 2020).
6. Schnall, J, Rajkhowa, A, Ikuta, K. Surveillance and monitoring of antimicrobial resistance: limitations and lessons from the GRAM project. *BMC Med.* (2019) 17:176. doi: 10.1186/s12916-019-1412-8
7. Aenishaenslin C, Häsler B, Ravel A, Parmley J, Stärk K, Buckeridge D. Evidence needed for antimicrobial resistance surveillance systems. *Bull World Health Organ.* (2019) 97:283-9. doi: 10.2471/BLT.18.218917
8. Houe H, Nielsen SS, Nielsen LR, Ethelberg S, Mølbak K. Opportunities for improved disease surveillance and control by use of integrated data on animal and human health. *Front Vet Sci.* (2019) 6:301. doi: 10.3389/fvets.2019.00301
9. Falzon LC, Alumasa L, Amanya F, Kang'ethe E, Kariuki S, Momanyi K, et al. One health in action: operational aspects of an integrated surveillance system for Zoonoses in Western Kenya. *Front Vet Sci.* (2019) 6:252. doi: 10.3389/fvets.2019.00252
10. Falzon L, Lechner I, Chantziaras I, Collineau L, Courcoul A, Filippitzi M, et al. Quantitative outcomes of a one health approach to study global health challenges. *EcoHealth.* (2018) 15:209–27. doi: 10.1007/s10393-017-1310-5
11. Bordier M, Delavenne C, Thuy Thi Nguyen D, Goutard FL, Hendrikx P. One health surveillance: a matrix to evaluate multisectoral collaboration. *Front Vet Sci.* (2019) 6:109. doi: 10.3389/fvets.2019.00109
12. Peyre M, Hoinville M, Njorogec J, Cameron A, Traon D, Goutard F, et al. The RISKSUR EVA tool (Survtool): a tool for the integrated evaluation of animal health surveillance systems. *Prev Vet Med.* (2019) 173:104777. doi: 10.1016/j.prevetmed.2019.104777
13. Calba C, Goutard FL, Hoinville L, Hendrikx P, Lindberg A, Saegerman C, et al. Surveillance systems evaluation: a systematic review of the existing approaches. *BMC Public Health.* (2015) 15:448. doi: 10.1186/s12889-015-1791-5
14. EMPRESTOOLS, Surveillance Evaluation Tool (SET). Available online at: http://www.fao.org/ag/againfo/programmes/en/empres/tools_SET.html (accessed October 1, 2020).
15. Bordier M, Uea-Anuwong T, Binot A, Hendrikx P, Goutard FL. Characteristics of one health surveillance systems: a systematic literature review. *Prev Vet Med.* (2018) 181:104560. doi: 10.1016/j.prevetmed.2018.10.005
16. NEOH. *EU Cost Action Network for Evaluation of One Health 'NEOH'(TD1404) Action Website.* Available online at: http://neoh.onehealthglobal.net/ (accessed October 1, 2020).
17. FAOa. *FAO Progressive Management Pathway for Antimicrobial Resistance (PMP-AMR).* Available online at: http://www.fao.org/antimicrobial-resistance/resources/tools/fao-pmp-amr/en/ (accessed October 1, 2020)
18. FAOb. *FAO Assessment Tool for Laboratories and AMR Surveillance Systems (ATLASS).* Available online at: http://www.fao.org/antimicrobial-resistance/resources/tools/fao-atlass/en/ (accessed October 1, 2020).
19. Aenishaenslin C, Häsler B, Ravel A, Parmley EJ, Mediouni S, Bennani H, et al. Evaluating the integration of one health in surveillance systems for antimicrobial use and resistance: a conceptual framework. *Front Vet Sci.* (2021) 8:611931. doi: 10.3389/fvets.2021.611931
20. Rüegg SR, Nielsen LR, Buttigieg SC, Santa M, Aragrande M, Canali M, et al. A systems approach to evaluate one health initiatives. *Front Vet Sci.* (2018) 5:23. doi: 10.3389/fvets.2018.00023
21. Nielsen LR, Alban, L, Ellis-Iversen, J, Mintiens, K, Sandberg, M. Evaluating integrated surveillance of antimicrobial resistance: experiences from use of three evaluation tools. *Clin Microbiol Infect.* (2019) 26:1606–1611. doi: 10.1016/j.cmi.2020.03.015
22. JPIAMR. Available online at: https://www.jpiamr.eu/supportedprojects/7th-call-results/ (accessed October 1, 2020).

Conflict of Interest: MB was involved in the development of ECoSur and LN was involved in the development of NEOH.

The remaining 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.

frontiers in Veterinary Science

BRIEF RESEARCH REPORT
published: 08 July 2021
doi: 10.3389/fvets.2021.618497

Antimicrobial Resistance Pilot Surveillance of Pigs and Chickens in Vietnam, 2017–2019

C. V. Tuat [1], P. T. Hue [1], N. T. P. Loan [1], N. T. Thuy [1], L. T. Hue [1], V. N. Giang [2], Vera I. Erickson [2] and Pawin Padungtod [2]*

[1] Department of Animal Health, Ministry of Agriculture and Rural Development, Hanoi, Vietnam, [2] Food and Agriculture Organization of the United Nations Country Office for Vietnam, Hanoi, Vietnam

OPEN ACCESS

Edited by:
Salome Dürr,
University of Bern, Switzerland

Reviewed by:
Agnes Agunos,
Public Health Agency of Canada, Canada
Anaïs Léger,
Federal Food Safety and Veterinary Office (FSVO), Switzerland

***Correspondence:**
Pawin Padungtod
pawin.padungtod@fao.org

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: 17 October 2020
Accepted: 14 April 2021
Published: 08 July 2021

Citation:
Tuat CV, Hue PT, Loan NTP, Thuy NT, Hue LT, Giang VN, Erickson VI and Padungtod P (2021) Antimicrobial Resistance Pilot Surveillance of Pigs and Chickens in Vietnam, 2017–2019. Front. Vet. Sci. 8:618497. doi: 10.3389/fvets.2021.618497

Antimicrobial use (AMU) and antimicrobial resistance (AMR) are a growing public health and economic threat in Vietnam. We conducted a pilot surveillance programme in five provinces of Vietnam, two in the south and three in the north, to identify antimicrobial resistance (AMR) in rectal swab samples from pigs and fecal samples from chickens at slaughter points during three different points in time from 2017 to 2019. *Escherichia coli* (*E. coli*) and non-typhoidal *Salmonella* (NTS) isolates were tested for antimicrobial susceptibility using disk diffusion assay for 19 antimicrobial agents belonging to nine antimicrobial classes and Etest for colistin (polymyxin). Almost all *E. coli* (99%; 1029/1042) and NTS (96%; 208/216) isolates were resistant to at least one antimicrobial agent; 94% (981/1042) of *E. coli* and 89% (193/216) of NTS isolates were multidrug-resistant (MDR). Higher proportions of *E. coli* and NTS isolated from chickens were resistant to all antimicrobial classes than those isolates from pigs. There was a significantly higher proportion of MDR NTS isolates from the southern provinces of Ho Chi Minh City and Long An ($p = 0.008$). Although there were increasing trends of NTS in proportion of resistance to fluoroquinolone over the three surveillance rounds, there was a significant decreasing trend of NTS in proportion of resistance to polymyxin ($p = 0.002$). It is important to establish an annual AMR surveillance program for livestock in Vietnam to assess the impact of interventions, observe trends and drive decision making that ultimately contributes to reducing AMR public health threat.

Keywords: pig, chicken, *Salmonella*, *Escherichia coli*, anti-bacterial agents, drug resistance, public health, livestock

INTRODUCTION

Antimicrobial use (AMU) and antimicrobial resistance (AMR) are a growing public health and economic threat in Vietnam and countries in southeast Asia (1). *Escherichia coli* (*E. coli*) isolated from pig and chicken farms in Vietnam had extremely high resistance to ampicillin and ciprofloxacin, and high resistance to gentamycin and colistin (2). A similar situation has also been observed in Cambodia (3). A very high proportion of non-typhoidal *Salmonella* (NTS), isolated from meat in the market in Vietnam was resistant to quinolone and beta-lactams (4). Overall, the use of antimicrobials in livestock production and poor biosecurity, especially on small farms, were associated with high levels of AMR in Vietnam (2, 5).

Resistance genes, resistant bacteria and antibiotic residues can spread to humans via direct contact with animals, wastewater, slurry, vegetables, and animal by-products (6, 7). Before the ban of antimicrobial growth promoters in 2018 in Vietnam, the most widely used in-feed antibiotics in chicken production were bacitracin, chlortetracycline and enramycin. In pig production the most used antibiotics were bacitracin, chlortetracycline and florfenicol (1).

The World Health Organization (WHO) has listed five antimicrobial classes of highest priority among the critically important antimicrobials (CIAs); cephalosporins (3rd, 4th, and 5th generations), glycopeptides, macrolides and ketolides, polymyxins, and quinolones (8). A 2019 study in Indonesia, Thailand, and Vietnam identified neomycin, colistin and amoxicillin in pig and chicken feeds, all of which are antimicrobials classified as critically important or highly important in treatment of human infections (9).

In 2017, Vietnam's Ministry of Agriculture and Rural Development (MARD) issued a national action plan for AMR and AMU in livestock and aquaculture in line with the Food and Agriculture Organization of the United Nations (FAO) Action Plan on AMR (10). One of the main activities under this plan was to establish and implement a national programme for the surveillance of AMR in animals and food (11). MARD assigned the Department of Animal Health as the focal agency for AMU and AMR management in livestock. In collaboration with Department of Animal Health, FAO, conducted a pilot surveillance to support the development of the national AMR surveillance programme and establish a baseline that could be used to track AMR level changes. This pilot surveillance was designed to estimate AMR in two commensal bacteria, *E. coli* and non-typhoid *Salmonella* (NTS), in pigs and chickens. We expected that the surveillance would also allow comparison of AMR spatially (between geographical regions) and temporally (between rounds of sampling) in pigs and chickens produced in Vietnam.

MATERIALS AND METHODS

The pilot surveillance was conducted in five provinces in Vietnam: three in the north, Hanoi, Hai Phong, Quang Ninh; and two in the south, Ho Chi Minh City and Long An. The first round of surveillance was conducted in August 2017, the second round in February 2019 and the third round in August 2019. The target population was chickens sold at wet markets and pigs at slaughter points.

The National Center for Veterinary Hygiene and Inspection (NCVHI) No.1 in Hanoi, which is an assigned laboratory for AMR surveillance, was assessed for technical capacity and biological material management before conducting the first round of the pilot surveillance using FAO Assessment Tool for Laboratory and AMR Surveillance Systems (ATLASS) in April 2017. NCVHI is also accredited by the ISO/IEC 17025 standard for conducting isolation and identification of *E. coli* and NTS.

For the sample size, we followed the European Food Safety Authority's target sample size of 170 isolates tested for each species (12). Seven pigs and seven chickens slaughter points (either at slaughterhouses or wet markets) with the highest number of animals processed in each region (north and south) were selected. NCVHI staff conveniently selected 25 pig rectal swabs from all holding pens, or 25 chicken droppings from all chicken cages from each slaughter points for sample collection. The total sample size of 350 for each species collected each round was assumed to yield at least 170 NTS isolates if the prevalence of NTS was 50% in pigs and chickens (13). All laboratory tests were performed at NCVHI No. 1 were based on protocols, including reference strains established by Department of Animal Health following FAO regional antimicrobial resistance surveillance and monitoring guidelines (14).

Samples for NTS were stored in a falcon tube containing 10 ml buffered peptone water at room temperature (25°C). Samples for *E. coli* were stored in a falcon tubes and kept cool (4°C) immediately after sampling. All *E. coli* or *Salmonella* isolates were stored at the laboratory, preserved in appropriate condition before conducting the antimicrobial susceptibility testing. Isolates to be tested and quality control strains were revived by using a nutrient agar medium. NTS isolates were not further characterized (serogrouping and serotyping). Antimicrobial susceptibility testing of *E. coli* and NTS isolated from pig and chicken fecal samples were conducted using the Kirby-Bauer disk diffusion test for 19 agents belonging to nine antimicrobial classes. Etest was used to determine resistance to colistin. *E. coli* and NTS isolates were classified as resistant using Clinical Laboratory Standard Institute (15) and European Committee on Antimicrobial Susceptibility Testing (www.EUCAST.org) breakpoints. Reference strains for testing quality control were used, including: *Salmonella typhimurium* American Type Culture Collection (ATCC) 14020 for identification of NTS; ATCC *E. coli* 25922 for identification of *E. coli*; *P. Aeruginosa* ATCC 27853 for cat-ion control; *Enterococcus faecalis* ATCC 29212 for thymidine control in the medium; the ATCC *E. coli* 25922 and the *K. pneumoniae* ATCC 700603 for antimicrobial susceptibility testing. A multidrug resistant (MDR) strain is defined as a strain's non-susceptibility to at least one agent in three or more antimicrobial classes (16). Enrofloxacin was classified as resistant if the zone diameter was $\leq$ 16 mm. For colistin, an Etest (AB Biodisk, Solna, Sweden),

TABLE 1 | Collection of pig and chicken samples during three rounds of antimicrobial resistance surveillance in five provinces in Vietnam, 2017–2019.

	Province	Pig	Chicken
Slaughter points	Hanoi	1	2
	Hai Phong	1	1
	Quang Ninh	1	-
	Ho Chi Minh City	2	1
	Long An	2	3
Animals sampled per slaughter points		25	25
Animals sampled per round		175	175
Total number of samples (three rounds)		525	525
Total number of samples tested		1,050	

a minimum inhibitory concentration (MIC) assay, was used with the criteria that isolates with MIC > 4 were classified as resistant. Proportions of resistance were compared using the chi-square test.

Significant levels of increasing or decreasing trends over the three rounds of sampling were determined using the score test for trend of resistant odds from round one to round three. A multivariable logistic regression model with slaughter points as a random effect was used to estimate odds ratio (OR) of resistance isolated from different species (pig/chicken), regions (north/south) and rounds (August 2017/February 2019/August 2019). We include rounds in the model to clarify the direction of the trend and differences between sampling rounds. Resistance to at least one agent in each antimicrobial class was used as an outcome variable. All variables were kept in the model to control for each other. All statistical tests were conducted at 0.05 significant level. All statistical analysis was performed using STATA (College Station, TX).

Samples and data were collected by the Department of Animal Health in Vietnam. Information on specific animals was collected from slaughterhouses and wet markets without identifying the owners' personal information.

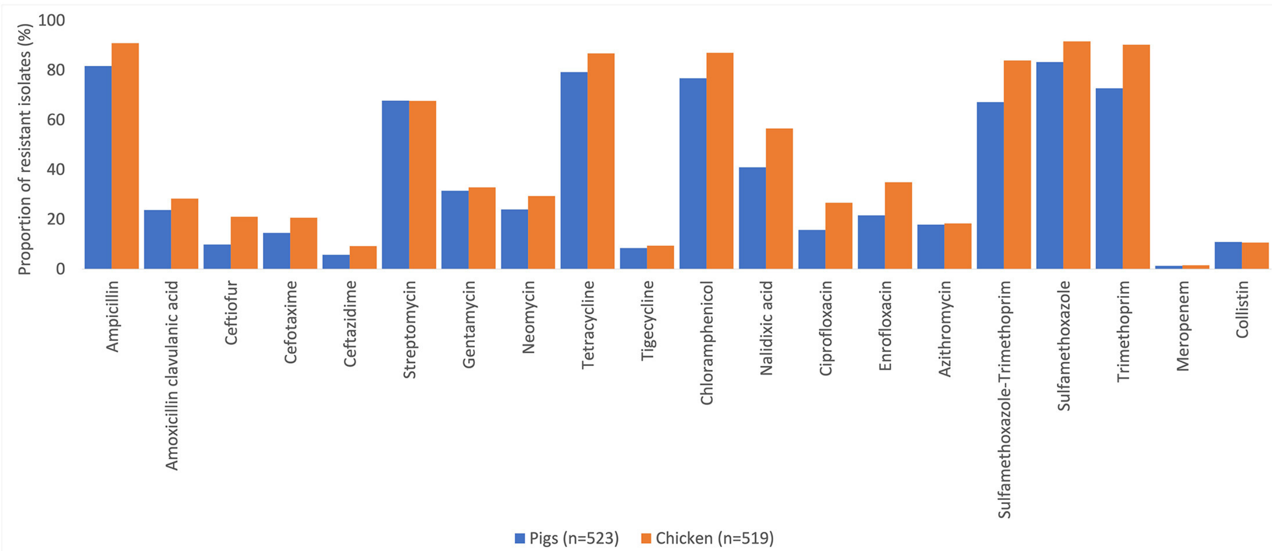


FIGURE 1 | Percentages of antimicrobial resistance in *Escherichia coli* in pig and chicken samples collected from five provinces in Vietnam, 2017–2019.

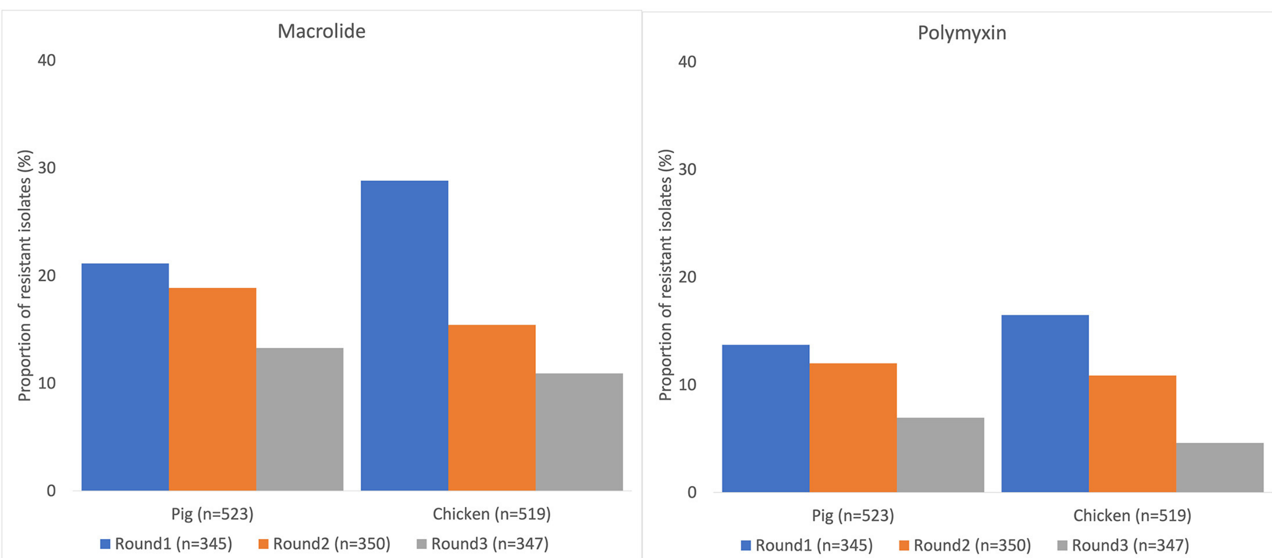


FIGURE 2 | Decreasing trend of *Escherichia coli* resistance to macrolide and polymyxin in pig and chicken samples collected from five provinces in Vietnam, 2017–2019.

TABLE 2 | Association between *Escherichia coli* resistance, species, region and round, Vietnam, 2017–2019.

Antimicrobial classes	Species		Region		Round				
	Chicken/pig		South/North		2/1		3/1		Trend *p*
	OR	*p*	OR	*p*	OR	*p*	OR	*p*	
Beta—lactam	2.2	<0.001	1.0	0.885	0.7	0.150	0.5	0.001	<0.001
Cephalosporin	1.7	0.001	0.6	0.001	2.0	<0.001	1.1	0.661	<0.001
Aminoglycosides	1.2	0.213	1.0	0.994	0.8	0.002	0.6	0.008	0.011
Tetracycline	1.7	0.006	0.9	0.667	0.3	<0.001	0.3	<0.001	<0.001
Phenicol	2.0	<0.001	1.4	0.049	0.8	0.156	0.9	0.686	<0.001
Fluoroquinolone	1.6	<0.001	0.8	0.087	0.8	0.190	0.6	0.001	<0.001
Macrolides	1.0	0.799	1.0	0.835	0.6	0.012	0.4	<0.001	0.001
Sulphonamides	2.6	<0.001	0.8	0.425	1.0	0.907	1.2	0.646	0.005
Carbapenems	1.2	0.778	0.5	0.193	0.9	0.778	-	-	0.591
Polymyxin	1.0	0.881	0.5	0.001	0.7	0.161	0.3	<0.001	<0.001
Extended-Spectrum Beta-Lactamases	2.2	<0.001	1.0	0.804	2.7	<0.001	3.4	<0.001	<0.001
Resistance to at least one agent	2.3	0.175	1.1	0.821	0.3	0.179	0.4	0.270	0.373
Multi-Drug Resistance	1.5	0.155	1.1	0.853	0.7	0.208	0.8	0.404	0.446

This table summarizes the between species and between geographical locations analyses; pig and north Vietnam (in bold fonts) were reference levels used. For the temporal analysis (between rounds), rounds 2 and 3 were compared to round 1 of sampling; trends with p values < = 0.05 indicate significant temporal trend over all three rounds using score test.

RESULTS

A total of 1,050 samples were tested (**Table 1**). The overall *E. coli* isolation rate was 99% (1042/1050) and 21% (216/1050) for NTS. There was significantly ($p < 0.001$) more NTS isolated from pigs (26%, 136/525) than chickens (15%, 80/525) while *E. coli* isolation rate in both pigs (100%, 523/525) and chickens (99%, 519/525) were not significantly different ($p = 0.156$). The isolation rates for *E. coli* (345/350, 350/350, 347/350; $p = 0.091$) and NTS (64/349, 80/350, 72/350; $p = 0.336$) were not significantly different when comparing the three surveillance rounds.

Resistance to at least one antimicrobial agent was found in 99% (1042/1050) of *E. coli* and 96% (216/1050) of NTS isolates. MDR was found in 94% (981/1042) of *E. coli* and 89% (193/216) of NTS isolates. Many of the *E. coli* isolates showed extremely high proportions of resistant with more than 70% of isolates being resistance to six antimicrobials tested (**Figure 1**). A high proportion of *E. coli* isolated from both chickens (95%, 494/519) and pigs (93%, 487/523) were MDR. A higher proportion of *E. coli* isolates from chicken were resistant to all antimicrobial classes, than those isolated from pigs. The proportion of MDR *E. coli* was not significantly different over the three surveillance rounds. The decreasing trend of *E. coli* resistance to macrolide ($p = 0.001$) and polymyxin ($p < 0.001$) is shown in **Figure 2**. When comparing the two southern and three northern provinces, there was a significantly lower proportion of *E. coli* with resistance to cephalosporin (OR = 0.6, $p = 0.001$) and polymyxin (OR = 0.5, $p = 0.001$) in the south compared to the north (**Table 2**).

Many of the NTS isolates showed high proportions of resistance (**Figure 3**). In NTS isolated from chickens, 95% (76/80) were MDR, while 86% (117/136) of NTS isolated from pigs were MDR. Higher proportions of NTS isolated from chickens were resistant to all antimicrobial classes tested than those isolates from pigs (**Table 3**). The decreasing trend of NTS resistance to macrolide ($p < 0.001$) and polymyxin ($p = 0.002$) is shown in **Figure 4**.

The proportion of MDR NTS isolated from pigs and chickens in the southern provinces was significantly higher (OR = 3.7, $p = 0.008$) than in the northern provinces (**Table 3**). When comparing the two provinces in the south to the three provinces in the north, there was a significantly higher proportion of resistant NTS to fluoroquinolones (OR = 3.0, $p = 0.001$), but a significantly lower proportion of resistance to cephalosporin (OR = 0.4, $p = 0.010$) (**Table 3**).

The median number of resistant antimicrobial classes in *E. coli* and NTS isolates from chickens was significantly ($p < 0.001$) higher than the median number in pigs (**Table 4**). There was a significantly higher proportion of MDR NTS isolates from the south (Ho Chi Minh city, Long An; $p = 0.008$) compared to the north (Hanoi, Hai Phong, Quang Ninh). Although there was an increasing trend of NTS in proportion of resistance to fluoroquinolone over the three surveillance rounds, there was a significant decreasing trend of NTS in proportion of resistance to polymyxin. Similar patterns were also observed in *E. coli*.

DISCUSSION AND CONCLUSION

Both *E. coli* and NTS detected in this study are commensals bacteria that do not cause disease in animals, although some of these strains can cause diseases in human. Overall, this pilot surveillance found almost all *E. coli* and NTS with resistant to at least one antimicrobial tested. A high proportion of *E. coli* and NTS were MDR. Considering resistance to the WHO's CIA, there was a low proportion of *E. coli* and NTS with resistance to third generation cephalosporin (ceftazidime); low to moderate with resistance to polymixin (colistin) and

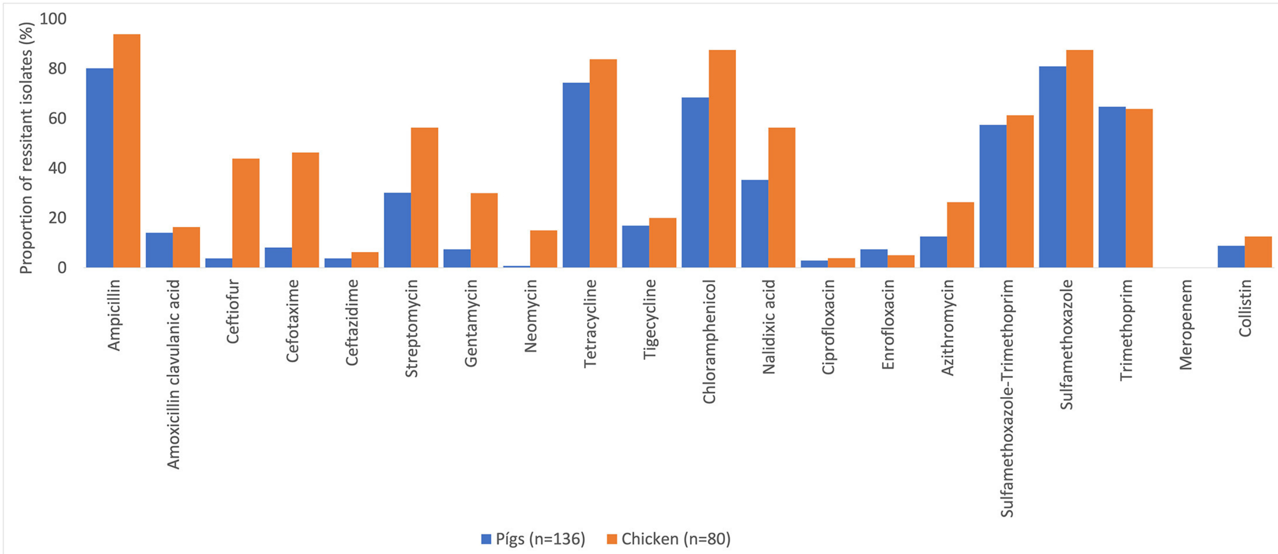


FIGURE 3 | Antimicrobial resistance in non-typhoidal *Salmonella* in pig and chicken samples collected from five provinces in Vietnam for 20 antimicrobials, 2017–2019.

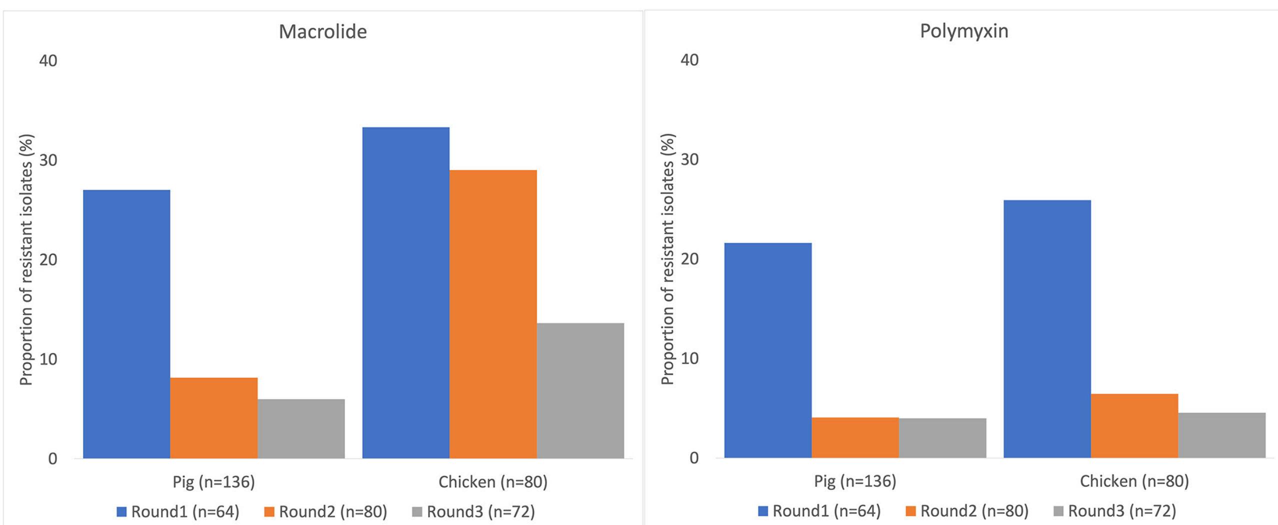


FIGURE 4 | Decreasing trend of non-typhoidal *Salmonella* resistance to macrolide and polymyxin in pig and chicken samples collected from five provinces in Vietnam, 2017–2019.

fluoroquinolone (ciprofloxacin); and moderate to high with resistance to macrolide (azithromycin). However, there was a decreasing trend of *E. coli* and NTS resistance to macrolide and polymyxin, shown by both regression and trend analysis, after the 2018 ban of antimicrobial growth promoters. A variety of resistance characteristics between *E. coli* and NTS were identified between the northern and southern provinces of Vietnam.

The prevalence of NTS isolated from pigs (26%, 136/525) and chickens (15%, 80/525) were much lower than the NTS prevalence identified at pig (65%) and chicken (31%) farms (13), and in pork (70%) and chicken meat (70%) sold at the market (4). However, the lower prevalence may have resulted from using individual samples collected from many different sources of animals at slaughter points as opposed to using environmental samples from farms or markets. Despite the lower prevalence, NTS was found in this study and could be potentially be transmitted to humans and cause disease via under cooked food. The proportion of MDR *Salmonella* in Vietnam detected in this study was much higher than those reported earlier in Vietnam (17), Thailand and Cambodia (18). We currently do not have any explanation for this difference, but further analysis comparing antimicrobial consumption among these countries may shed some light on this issue. *Salmonella*, with resistance to third generation cephalosporin, one of WHO highest priority CIAs, was reported earlier in Vietnam with an increasing proportion of resistance from <1% in 2015 to 4% in 2018 and up to 22%

TABLE 3 | Association between non-typhoidal *Salmonella* resistance, species, region and round, Vietnam, 2017–2019.

Antimicrobial classes	Species		Region		Round				
	Chicken/pig		South/North		2/1		3/1		Trend *p*
	OR	*p*	OR	*p*	OR	*p*	OR	*p*	
Beta—lactam	4.4	0.008	1.8	0.143	0.8	0.636	0.4	0.077	<0.001
Cephalosporin	22.9	<0.001	0.4	0.010	0.7	0.267	0.3	<0.001	<0.001
Aminoglycosides	4.1	<0.001	0.6	0.294	25.2	<0.001	3.4	0.049	<0.001
Tetracycline	1.7	0.249	1.6	0.226	5.8	0.009	0.4	0.038	<0.001
Phenicol	3.2	0.004	1.8	0.097	5.0	0.002	0.6	0.243	<0.001
Fluoroquinolone	2.9	0.001	3.0	0.001	4.9	<0.001	3.2	0.004	<0.001
Macrolides	2.5	0.016	0.4	0.029	0.5	0.082	0.2	0.003	<0.001
Sulphonamides	1.5	0.387	1.4	0.441	0.9	0.802	0.6	0.308	0.557
Carbapenems	-	-	-	-	-	-	-	-	-
Polymyxin	1.4	0.506	0.7	0.390	0.2	0.004	0.1	0.003	0.002
Extended-Spectrum Beta-Lactamases	18.8	<0.001	0.3	0.026	41.1	<0.001	1.5	0.637	<0.001
Resistance to at least one agent	1.4	0.685	2.0	0.368	-	-	0.2	0.085	0.129
Multi-Drug Resistance	2.9	0.074	3.7	0.008	0.5	0.354	0.2	0.020	0.001

This table summarizes the between species and between geographical locations analyses; pig and north Vietnam (in bold fonts) were reference levels used. For the temporal analysis (between rounds), rounds 2 and 3 were compared to round 1 of sampling; trends with p values < = 0.05 indicate significant temporal trend over all three rounds using score test.

TABLE 4 | Distribution of multidrug resistant isolates collected from pig and chicken samples during three rounds of antimicrobial resistance surveillance in five provinces in Vietnam, 2017–2019.

Number of classes	*Escherichia coli*				Non-typhoidal *Salmonella*			
	Pig (*n* = 514)		Chicken (*n* = 515)		Pig (*n* = 129)		Chicken (*n* = 78)	
	No.	%	No.	%	No.	%	No.	%
1	11	2.1	8	1.6	7	5.4	1	1.3
2	16	3.1	13	2.5	6	4.7	1	1.3
3	39	7.6	15	2.9	11	8.5	3	3.8
4	77	15	61	11.8	51	39.5	18	23.1
5	160	31.1	121	23.5	29	22.5	6	7.7
6	129	25.1	147	28.5	20	15.5	10	12.8
7	59	11.5	106	20.6	4	3.1	28	35.9
8	20	3.9	42	8.2	1	0.8	11	14.1
9	3	0.6	2	0.4	0	0	0	0
10	0	0	0	0	0	0	0	0
Median	5		6		4		6	

(48/216) in this study. Similarly, resistance to fluoroquinolone, another WHO priority CIA, in this and more recent studies, is much higher than earlier reported (4, 13).

We found the proportion of *E. coli* with resistance to colistin in both pigs and chicken (11%, 112/1,042) was lower than other studies (22–24%) had reported earlier (2), corresponding to the lower proportion of Extended-Spectrum Beta-Lactamases (ESBL) producing *E. coli* also found in this study. A study in Vietnam published in 2018 showed a high occurrence of ESBL producing *E. coli* in both pig farmers and pigs that could pose a risk of transmission of these bacteria from pig farms to the community (19).

This pilot surveillance study had several limitations. The model for the sample size was from the European Food Safety Authority that stated the optimal sample size should be 170 positive isolates of *E. coli* and NTS for each bacterium in each animal species. However, we only found 80 positive NTS isolates in chicken, which is arguably not a strong enough sample size to evaluate resistance in NTS. We also assumed that the 25 samples from each slaughter point would represent animals from 25 different locations. However, animals could not be traced back to the farm of origin; this could have led to clustering of samples from the same farms. Fecal samples were collected from conveniently selected droppings from cages in the wet markets. The microbial status of the bird cages may have impacted the results due to inadequate cleaning and disinfection. Although using the disk diffusion test is an affordable method to assess resistance, this method does not provide the MIC to allow for subsequent analysis, especially when different interpretive criteria are used or the criteria change (14). Further typing of NTS found in this study can clarify the risk poses.

In conclusion, the observed dynamic of resistance of *E. coli* and NTS to many antimicrobials warrant the development of a national AMR surveillance programme to monitor the situation and support AMU management policy development. As our findings differed between the two geographical areas, management may need to be customized for the northern and southern areas of the country. The decreasing trend of resistance to WHO's highest priority critically important antimicrobials detected by the surveillance programme can also be used to strengthen the implementation of existing AMU management policy such as banning of antimicrobial growth promoters and advocate for further usage reduction policy such as banning of prophylaxis use. AMR is a public health concern, requiring cross-sectoral collaboration. From a public health perspective, it is especially important to monitor WHO's highest priority critically important antimicrobial classes in animals as well as in humans. We recommend that a national AMR surveillance program for livestock be established in Vietnam. Annual surveillance makes it possible to assess the impact of interventions, observe trends and drive decision making that ultimately contributes to reducing the public health threat from AMR. This antimicrobial resistance data in livestock, generated by the Vietnam Department of Animal Health, has contributed to the global antimicrobial resistance surveillance database and can be used for joint analysis with human health surveillance data under the One Health approach. Future One Health surveillance design, involving human health, animal health and the private sector can be developed through the identification of appropriate levels of collaboration, depending on the expected positive impacts on the value of surveillance (20). The multi-sectoral AMR surveillance, leading to the harmonization and combination of data from different sources, could improve knowledge on transmission routes and risk factors related to AMR in human, animal and environment (21). Specifically, the AMR surveillance programme can be included under the next phase of the national action plan for the management of AMU and monitoring of AMR 2021–2025. The national action plan would provide a legal basis for mobilizing resource from central and provincial authorities to support the surveillance activities and ensure sustainability of the surveillance programme.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because The surveillance was conducted by a national competent authority for animal health.

AUTHOR CONTRIBUTIONS

CT, NT, LH, VG, and PP conceived and designed study. CT, PH, and NL conducted field sample collection and laboratory testing. CT, PH, NL, VE, and PP contributed to data analysis. CT, VE, and PP contributed to writing and editing the manuscript. All authors contributed to the article revision and approved the submitted version.

FUNDING

This work was conducted with financial support from the United States Agency for International Development (USAID) grant number GHA-G-00-06-00001, through the Food and Agriculture Organization of the United Nations.

ACKNOWLEDGMENTS

We would like to acknowledge the technical support from the Oxford University Clinical Research Unit (OUCRU), the Director and staff of the microbiology laboratory of the National Center for Veterinary Hygiene Inspection No I, Sub-Department of Animal Health in Hanoi, Hai Phong, Quang Ninh, Ho Chi Minh City and Long An, and the owners of pig slaughterhouses and chicken vendors who assisted us in sample collection and provided essential information.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.618497/full#supplementary-material

REFERENCES

1. Nhung NT, Cuong NV, Thwaites G, Carrique-Mas J. Antimicrobial usage and antimicrobial resistance in animal production in Southeast Asia: a review. *Antibiotics (Basel).* (2016) 5:37. doi: 10.3390/antibiotics5040037
2. Nguyen NT, Nguyen HM, Nguyen CV, Nguyen TV, Nguyen MT, Thai HQ, et al. Use of colistin and other critical antimicrobials on pig and chicken farms in Southern Vietnam and its association with resistance in commensal *Escherichia coli* bacteria. *Appl Environ Microbiol*. (2016) 82:3727–35. doi: 10.1128/AEM.00337-16
3. Strom G, Boqvist S, Albihn A, Fernstrom LL, Andersson Djurfeldt A, Sokerya S, et al. Antimicrobials in small-scale urban pig farming in a lower middle-income country - arbitrary use and high resistance levels. *Antimicrob Resist Infect Control*. (2018) 7:35. doi: 10.1186/s13756-018-0328-y
4. Nhung NT, Van NTB, Cuong NV, Duong TTQ, Nhat TT, Hang TTT, et al. Antimicrobial residues and resistance against critically important antimicrobials in non-typhoidal *Salmonella* from meat sold at wet markets and supermarkets in Vietnam. *Int J Food Microbiol*. (2018) 266:301–9. doi: 10.1016/j.ijfoodmicro.2017.12.015
5. Nguyen VT, Carrique-Mas JJ, Ngo TH, Ho HM, Ha TT, Campbell JI, et al. Prevalence and risk factors for carriage of antimicrobial-resistant *Escherichia coli* on household and small-scale chicken farms in the Mekong Delta of Vietnam. *J Antimicrob Chemother*. (2015) 70:2144–52.

6. Holmes AH, Moore LS, Sundsfjord A, Steinbakk M, Regmi S, Karkey A, et al. Understanding the mechanisms and drivers of antimicrobial resistance. *Lancet*. (2016) 387:176–87. doi: 10.1016/S0140-6736(15)00473-0
7. Graham DW, Bergeron G, Bourassa MW, Dickson J, Gomes F, Howe A, et al. Complexities in understanding antimicrobial resistance across domesticated animal, human, and environmental systems. *Ann N Y Acad Sci USA*. (2019)1441:17–30. doi: 10.1111/nyas.14036
8. WHO. *Critically Important Antimicrobials for Human Medicine 6th revision2019*. Available online at: https://www.who.int/foodsafety/publications/antimicrobials-sixth/en/
9. Coyne L, Arief R, Benigno C, Giang VN, Huong LQ, Jeamsripong S, et al. Characterizing antimicrobial use in the livestock sector in three South East Asian Countries (Indonesia, Thailand, and Vietnam). *Antibiotics (Basel)*. (2019) 8:33. doi: 10.3390/antibiotics8010033
10. FAO. *The FAO action plan on antimicrobial resistance 2016-2020*. (2016). Available online at: http://www.fao.org/3/a-i5996e.pdf
11. MARD. National action plan for management of antibiotic use and control of antibiotic resistance in livestock production and aquaculture. In: *Development MoAaR*. Hanoi: Ministry of Agriculture and Rural Development (MARD) (2017).
12. EFSA. Technical specifications on harmonised monitoring of antimicrobial resistance in zoonotic and indicator bacteria from food-producing animals and food. *EFSA J*. (2019) 17:5709. doi: 10.2903/j.efsa.2019.5709
13. Tu LT, Hoang NV, Cuong NV, Campbell J, Bryant JE, Hoa NT, et al. High levels of contamination and antimicrobial-resistant non-typhoidal *Salmonella* serovars on pig and poultry farms in the Mekong Delta of Vietnam. *Epidemiol Infect*. (2015) 143:3074–86. doi: 10.1017/S0950268815000102
14. FAO. *Monitoring and Surveillance of Antimicrobial Resistance in Bacteria From Healthy Food Animals Intended for Consumption*. (2019). Available online at: http://www.fao.org/3/ca6897en/CA6897EN.pdf
15. CLSI, editor. *Performance Standards for Antimicrobial Disk and Dilution Susceptibility Testd for Bacteria Isolated from Animals*. 4th ed. Wayne, PA: Clinical Laboratory Standard Institute (2013).
16. Magiorakos AP, Srinivasan A, Carey RB, Carmeli Y, Falagas ME, Giske CG, et al. Multidrug-resistant, extensively drug-resistant and pandrug-resistant bacteria: an international expert proposal for interim standard definitions for acquired resistance. *Clin Microbiol Infect*. (2012) 18:268–81. doi: 10.1111/j.1469-0691.2011.03570.x
17. Nguyen DT, Kanki M, Nguyen PD, Le HT, Ngo PT, Tran DN, et al. Prevalence, antibiotic resistance, and extended-spectrum and AmpC beta-lactamase productivity of *Salmonella* isolates from raw meat and seafood samples in Ho Chi Minh City, Vietnam. *Int J Food Microbiol*. (2016) 236:115–22. doi: 10.1016/j.ijfoodmicro.2016.07.017
18. Trongjit S, Angkititrakul S, Tuttle RE, Poungseree J, Padungtod P, Chuanchuen R. Prevalence and antimicrobial resistance in *Salmonella enterica* isolated from broiler chickens, pigs and meat products in Thailand-Cambodia border provinces. *Microbiol Immunol*. (2017) 61:23–33. doi: 10.1111/1348-0421.12462
19. Dang STT, Bortolaia V, Tran NT, Le HQ, Dalsgaard A. Cephalosporin-resistant *Escherichia coli* isolated from farm workers and pigs in northern Vietnam. *Trop Med Int Health*. (2018) 23:415–24. doi: 10.1111/tmi.13054
20. Bordier M, Binot A, Pauchard Q, Nguyen DT, Trung TN, Fortane N, et al. Antibiotic resistance in Vietnam: moving towards a One Health surveillance system. *BMC Public Health*. (2018) 18:1136. doi: 10.1186/s12889-018-6022-4
21. Queenan K, Hasler B, Rushton J. A One Health approach to antimicrobial resistance surveillance: is there a business case for it? *Int J Antimicrob Agents*. (2016) 48:422–7. doi: 10.1016/j.ijantimicag.2016.06.014

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.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 15 July 2021
doi: 10.3389/fvets.2021.661459

Added Value of Meat Inspection Data for Monitoring of Dairy Cattle Health in the Netherlands

Anouk M. B. Veldhuis [1]*, *Debora Smits* [1], *Martijn Bouwknegt* [2], *Heleen Worm* [1] and *Gerdien van Schaik* [1,3]

[1] Royal GD, Deventer, Netherlands, [2] Vion, Boxtel, Netherlands, [3] Department of Population Health Sciences, Faculty of Veterinary Medicine, Utrecht University, Utrecht, Netherlands

Meat inspection records of one large cattle slaughterhouse were analyzed to evaluate the added value of slaughterhouse data for cattle health surveillance in the Netherlands. Data were available from January 2015 to September 2018, consisting of 467,361 meat inspection records. Analyses included (1) an assessment of the representativeness of the cattle herds in the slaughterhouse data in relation to the cattle herd population in the Netherlands, and (2) multivariable analyses to quantify associations between meat inspection findings and farm of origin characteristics, and the trends in time of the findings in slaughtered cattle. Ninety percent of the meat inspection records originated from dairy cattle therefore this paper only presents the results of dairy herds ($N = 422,194$ cattle). The dairy herds in the slaughterhouse data seemed representative for the Dutch dairy population although their regional coverage differed from the distribution of dairy herds in the Netherlands. Non-dairy herds were underrepresented in the slaughterhouse data which stresses the importance of the inclusion of data from other slaughterhouses that may be more specialized in slaughtering beef cattle. Inspection records were categorized into 15 indicators related to ante-mortem and post-mortem findings. Following multivariable analyses, seven indicators were deemed of added value to existing cattle health surveillance components, as they provided either new information or information regarding specific health problems.

Keywords: meat inspection, surveillance, cattle, health, trend analysis

OPEN ACCESS

Edited by:
Bouda Vosough Ahmadi, European Commission for the Control of Foot and Mouth Disease (EuFMD), Italy

Reviewed by:
László Özsvári, University of Veterinary Medicine Budapest, Hungary
Liza Rosenbaum Nielsen, University of Copenhagen, Denmark
Margret Krieger, University of Kassel, Germany

***Correspondence:**
Anouk M. B. Veldhuis
a.veldhuis@gdanimalhealth.com

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: *30 January 2021*
Accepted: *16 June 2021*
Published: *15 July 2021*

Citation:
Veldhuis AMB, Smits D, Bouwknegt M, Worm H and van Schaik G (2021) Added Value of Meat Inspection Data for Monitoring of Dairy Cattle Health in the Netherlands. Front. Vet. Sci. 8:661459. doi: 10.3389/fvets.2021.661459

INTRODUCTION

Since 2002, a national cattle health surveillance system is in place in the Netherlands that consists of, amongst other surveillance components, a trend analysis surveillance component ("TASC") to monitor trends and developments in cattle health using routine census data (1). Briefly, stakeholders are informed on trends in key monitoring indicators such as mortality, fertility and udder health based on quarterly analyses of census data sources. When deemed relevant, additional in-depth analysis are performed to improve the models or to explore the potential of new data sources that could capture indicators of cattle health. The current study was carried out to assess the added value of meat inspection data in this context.

Cattle sent to slaughter undergo ante-mortem (AM) and post-mortem (PM) inspection by an official veterinarian or auxiliary meat inspector, to detect lesions that represent food-borne zoonotic infections. For example, PM meat inspection provides an important mechanism for detecting bovine tuberculosis (bTB) infections in cattle herds through the detection of bTB-like granulomas (2). In addition, meat inspection enables sentinel surveillance for animal health and welfare issues for which clinical surveillance is of limited sensitivity, such as foot and leg disorders and liver fluke infections (3). Given the systematic collection, its pre-diagnostic nature and large coverage, population-level meat inspection data has the potential to be a source of meaningful animal health information. Previous studies on slaughterhouse data revealed that certain characteristics of slaughtered cattle, such as sex and age of the animal and mortality rate in the herd of origin, are risk factors for partial, or whole carcass condemnation (4, 5). Analyzing data of condemned cattle carcasses could therefore be used to inform a risk-based surveillance approach of cattle health. Besides condemnation, changes in the trend of more specific AM- and/or PM-findings could reflect the occurrence of health disorders in the wider cattle population.

To evaluate the added value of slaughterhouse data for the cattle trend analysis surveillance component in the Netherlands, inspection results of one large cattle slaughterhouse were analyzed in this study. The study objective was 2-fold: (a) to assess whether the study population in the slaughterhouse data was representative for the target population (i.e., dairy and non-dairy herds in the Netherlands), and (b) to assess whether the trend in meat inspection findings and their association with characteristics of the farm of origin yields relevant input for the monitoring of trends in cattle health.

MATERIALS AND METHODS

Meat Inspection Data

In the Netherlands, up to 650,000 adult cattle and over 1.5 million veal calves were sent to slaughter per year between 2015 and 2018 (6). Veal calves are mainly slaughtered in specialized slaughterhouses. A dataset with demographic and health related data of 467,361 adult cattle originating from Dutch farms and slaughtered between January 1, 2015 and September 30, 2018 was available from a cattle slaughterhouse located in the south of the Netherlands. These animals undergo AM- and PM inspection by official veterinarians or auxiliary meat inspectors, i.e., employees of an independent external organization (referred to as "meat inspection" from this point forward). The meat inspection is performed according to the specific rules for official controls on products of animal origin laid down in Regulation (EC) 854/2004 of the European Parliament. The dataset comprised herd of origin, animal identification, sex, age, signs observed during AM and PM inspection and reasons for condemnation of each animal. Herd and animal identification numbers were anonymised by an external enterprise prior to analyses.

Data Analysis

Validation of Representativeness

For each herd in the dataset, the number of slaughtered cattle was aggregated by quarter of the year. These data were then merged with other routinely collected datasets containing herd type (dairy/non-dairy), herd size, region, on-farm cattle movements, and herd health certification statuses. These datasets were made available by nationally operating data collecting organizations and comprised the whole cattle population in the Netherlands. All data were anonymised by an external enterprise prior to analysis. More details on these data can be found in (1). The aforementioned herd characteristics were compared between the target population and the study population to assess the representativeness of the study population. About 90% of the meat inspection records originated from dairy herds. This paper therefore only presents the results of dairy herds.

Classification of Meat Inspection Findings

During the study period, 53 unique AM-findings and 79 unique PM-findings were recorded. A full list of the AM- and PM-findings is available upon request from the corresponding author. To identify meaningful trends and associations, AM-findings and PM-findings were categorized in 22 AM- and PM-categories using expert consultation. The team of experts consisted of a cattle veterinarian, a zootechnical specialist, an employer of the slaughterhouse and an employer of the competent authority responsible for the meat inspection in the slaughterhouse. "No AM-findings" and "No PM-findings" were added as additional categories as they potentially represent favorable animal health.

Multivariable Analyses

Statistical analyses were performed using STATA/SE version 15.1 software. For each herd, the number of slaughtered cattle with a finding in a specific category i was calculated per quarter t. Multivariable analyses where then conducted to quantify associations between characteristics of the herd of origin (i.e., the explanatory variables) and the herd-level frequency of AM- and PM-findings of each category of findings. Characteristics of the farm of origin were based on routinely collected census-data and included herd size, region, herd health certification statuses for endemic diseases [Salmonellosis, Leptospirosis, Bovine Viral Diarrhea Virus (BVDV), Bovine Herpes Virus-1 (BHV-1), and Para tuberculosis], antibiotic usage, annual replacement rate, farming system (open/closed), standardized milk production level (expressed as mean yearly net revenue per cow per herd), and average age of the slaughtered cattle (**Table 1**). More details on these data are described by Santman-Berends et al. (1). Slaughter cow prices, replacement cow prices and milk prices were retrieved from (7) and included as national averages per quarter of the year. Season, milk- and feed prices and quarter of the year were forced in the model as potential confounders. Independent continuous variables were categorized into four categories (10% smallest, 40% smaller, 40% larger, and 10% largest). For the independent categorical variables, the mean of the whole study population was included as the reference category). A population averaged panel-data model (xtgee) was fitted on each category of findings (i.e., the dependent variables) using a negative binomial distribution, a log link function, the unique herd identifier as panel variable, the year-quarter as time variable, the number of slaughtered cattle per herd per quarter as exposure variable and an independent correlation structure, in accordance with existing models of

TABLE 1 | Characteristics of dairy herds in the slaughterhouse dataset that were used as independent variables in the multivariable analyses to quantify associations between herd characteristics and the herd-level frequency of AM- and PM-findings amongst slaughtered cattle in one Dutch slaughterhouse (N = 10,406 dairy herds).

Characteristic	Category	Mean/Frequency
Quarter-year	1–15	n.a.
Age at slaughter (months)	Continuous	65.3
Antibiotic use in cattle 1–2 years of age (% of herds)	No	86%
	Yes	14%
Antibiotic use in cattle >2 years of age in mean Defined Daily Dose Animal (DDDA)	10% herds with lowest DDDA	0.32
	40% herds with lower DDDA	1.81
	40% herds with higher DDDA	3.55
	10% herds with highest DDDA	5.62
BHV-1 status (% of herds)	Free	38.3%
	Non-free or unknown	61.7%
BVD status (% of herds)	Free	45.4%
	Non-free or unknown	54.6%
Paratuberculosis status (% of herds)	Unsuspected	80.5%
	Suspected	19.5%
Salmonella status (% of herds)	Unsuspected	93.1%
	Suspected	6.9%
Milk price/kg	Continuous	€0.34
Slaughter cow price/kg	Continuous	€2.82
Replacement cow price#	Continuous	€928
Annual cattle replacement rate (mean % per herd)	10% lowest replacement	14.9%
	40% lower replacement	22.3%
	40% higher replacement	29.7%
	10% highest replacement	41.5%
Purchase of cattle in the previous year (% of herds)	Yes, >2 cattle/year	38.2%
	Yes, 1–2 cattle/year	10.5%
	No	51.2%
Season	Winter (Jan-Mar)	27.2%
	Spring (Apr-Jun)	23.8%
	Summer (Jul-Sep)	27.4%
	Autumn (Oct-Dec)	21.6%
Milk production level at herd level (mean yearly net revenue+; € per cow)	10% lowest	€1.577
	40% lower	€2.058
	40% higher	€2.393
	10% highest	€2.706
Herd size (mean number of cattle >2 years of age)	10% smallest herds	33.0
	40% smaller herds	69.9
	10% larger herds	122.5
	10% largest herds	244.8
Location of herd (province*) (% of herds)	Drenthe (North)	3.8%
	Flevoland (North)	2.1%
	Friesland (North)	7.0%
	Groningen (North)	3.2%
	Overijssel (East)	10.7%
	Gelderland (East)	15.7%
	N-Holland (West)	4.6%
	Utrecht (West)	8.3%
	Z-Holland (West)	10.0%
	Limburg (South)	5.4%
	N-Brabant (South)	26.5%
	Zeeland (South)	2.7%

#*Dairy cows, 1st class, producer price per animal.*
+*Standardized milk production (Dutch Royal Cattle Syndicate (CRV), Arnhem, the Netherlands).*
**The region in the Netherlands where the province is located is mentioned for clarity.*

TABLE 2 | Characteristics of dairy herds in the slaughterhouse dataset (study population) and all dairy herds in the Netherlands (target population) between January 2015 and September 2018.

	Herd size (mean)			Farming system	Herd health status	
	0–1 year	1–2 year	>2 year	Closed	BVD-free	BHV-1-free
Target population ($N = 17,263$)	36	29	103	52%	43%	38%
Study population ($N = 10,406$)	41	32	113	51%	45%	38%

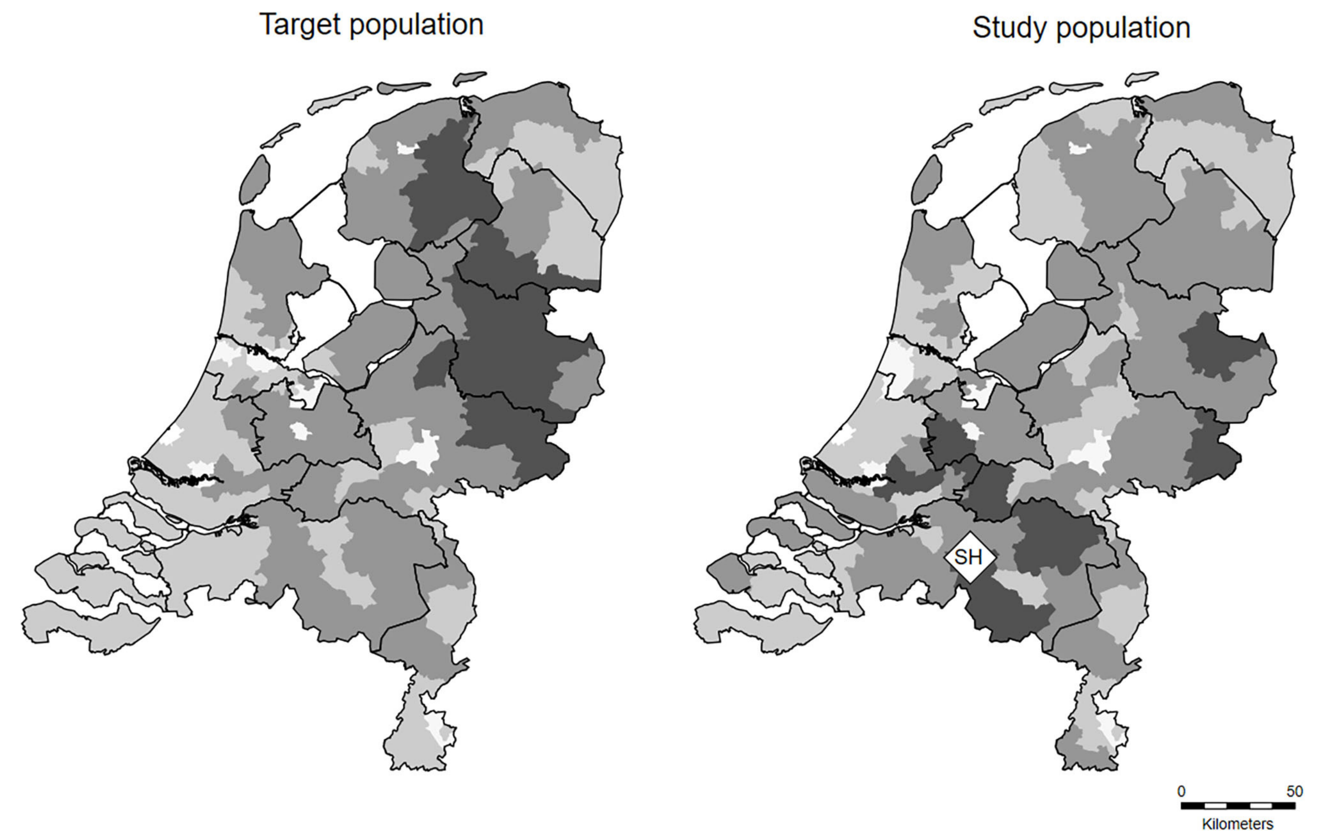


FIGURE 1 | Regional distribution of dairy herds in the target population and the study population per two-digit postal district over the period 2015–2018, with the slaughterhouse of study indicated with a diamond symbol ("SH"). Increasing color intensity of areas correspond with increasing cattle herd density.

animal health indicators in the TASC (1). The model can be formulated as:

$$\ln\left(y_{it}\right) = \mu_t + \beta_1 X_{1it} + \ldots + \beta_n X_{nit} + \varepsilon_{it} \quad (1)$$

Where:

$\ln\left(y_{it}\right)$ = natural logarithm of the number of cattle with a finding of category x in herd i in quarter t
μ_t = intercept for quarter t
$\beta_{1,\ldots n} X_{1,\ldots n\ it}$ = independent variable term for herd i in quarter t, for independent variables $1,\ldots n$ as described in **Table 1**.
ε_{it} = random error for herd i in quarter t

Associations between frequencies of AM- or PM-findings and independent variables were expressed as exponentiated coefficients (i.e., incidence rate ratios; IRR). For example: an explanatory variable with an IRR of 1.11 means that a unit increase in the explanatory variable corresponds to an increase of 11% in the number of cattle with a finding of category × per herd per quarter. Statistical significant IRR's ≤ 0.8 or ≥ 1.25 were deemed epidemiologically relevant.

RESULTS

Representativeness

About 90% of the meat inspection records originated from dairy herds ($N = 10,406$ herds, $n = 422,194$ slaughtered cattle). Inspection of the characteristics of these herds in relation to the overall dairy cattle population lead to the conclusion that the dairy herds in the slaughterhouse data were sufficiently representative for the Dutch dairy population (**Table 2**). However, the regional distribution of the dairy herds in the slaughterhouse data was skewed toward the southern region, probably due to the location of the slaughterhouse in the south of the Netherlands (**Figure 1**).

Descriptive Results

AM-findings were less common than PM-findings (**Table 3**). About 92% of the slaughtered cattle had no AM-finding and 45% of the slaughtered cattle had no PM-finding. AM-categories that were not further analyzed due to their very low frequency were findings related to the lung/heart, body condition, locomotion, skin/mucosa, udder, birth canal, digestion, and welfare. PM-findings related to liver, pulmonary/peritoneal membrane, and integumentary lesions were most common amongst the PM-categories. PM-findings related to the back and neck were omitted from further analyses due to their low frequency of occurrence amongst PM-categories.

TABLE 3 | Mean yearly percentage of slaughtered cattle with an AM- or PM-finding per category in one large Dutch slaughterhouse between January 1, 2015 and September 30, 2018. Categories that were not further analyzed are displayed in gray. N = 125.006 slaughtered cattle per year.

AM-category	%	PM-category	%
Body condition	0.99	Condemnation	2.46
Lung/heart	0.20	Liver fluke	6.41
Locomotion	0.59	Liver (except liver fluke)	11.86
Skin/mucosa	1.82	Lungs	7.82
Hygiene	4.01	Pulmonary membrane/peritoneum	14.20
Udder	0.08	heart	3.03
Birth canal	0.00	Udder	9.12
Digestion	0.30	Kidneys	4.82
Welfare	0.01	Lesions of the integumentary system	10.15
		Back	0.57
		Neck	2.06
		Round/buttock region	6.62
		Gastrointestinal tract	2.40
No AM-findings	92.48	No PM-findings	45.41

Multivariable Results

Associations With AM-Findings and Trend in Time

Results of the multivariable analyses of AM-findings are summarized in **Table 4**. Only statistical significant associations with a IRR ≤0.8 or ≥1.25 are shown. A complete overview of all associations is provided in **Supplementary Table 1**. The proportion of slaughtered cattle with an AM-finding related to hygiene varies a lot in time, which could not be captured well by the model (**Figure 2**). Due to this suboptimal fit of the model, the results of the AM-finding "hygiene" should be interpreted with caution. The proportion of slaughtered cattle in which no AM-findings were found shows an increasing trend in time (**Figure 3**). There were no epidemiologically relevant associations with explanatory variables (**Table 4**).

TABLE 4 | Results of multivariable analyses of AM-findings amongst slaughtered cattle from dairy herds between January 1, 2015 and September 30, 2018, in incidence ratios (IRR) and 95% confidence intervals. Only associations with a p-value <0.05 that met the relevance criteria (IRR ≤0.8 or ≥1.25) are shown (N = 78,366).

	AM-category	Hygiene	No AM-finding
Explanatory variable		**IRR**	**IRR**
Slaughter cow price (€/kg)		3.57 (2.81–4.54)	–
Season			
Mean	Ref.	Ref.	
	Winter (Jan-Mar)	1.51 (1.47–1.56)	–
	Spring (Apr-Jun)	0.52 (0.50–0.55)	–
	Summer (Jul-Sep)	0.70 (0.68–0.73)	–
	Autumn (Oct-Dec)	1.80 (1.72–1.90)	–

Associations With PM-Findings and Trend in Time

Results of the multivariable analyses of PM-findings are summarized in **Table 5**. Only statistical significant associations with a IRR ≤0.8 or ≥1.25 are shown. A complete overview of all associations is provided in **Supplementary Table 2**. Due to the large number of meat inspection categories analyzed, only a selection of the trends in time and relevant associations are described below.

The proportion of cattle with the PM-finding "condemnation" gradually decreased in time (**Figure 4**). Cattle from small herds had a lower proportion of carcass condemnation (IRR = 0.74 for the 10% smallest herds) and cattle from large herds had a higher proportion of carcass condemnation (IRR = 1.26 for the 10% largest herds). To illustrate this: the 10% largest herds had 26% more cattle sent to slaughter with carcass condemnation than the average herd in the dataset. Herds from the northern provinces Drenthe, Friesland and Groningen had a lower proportion carcass condemnations than the average farm (IRR = 0.46–0.79). Herds from central and southern provinces had a higher proportion of carcass condemnations (IRR = 1.26–1.50).

PM-findings categorized under "lungs" mainly represent pneumonia. An increase in slaughter cow price was associated with a lower proportion of cattle with a PM-finding related to lungs (IRR = 0.78). The proportion of cattle with a PM-finding related to lungs was decreasing until mid-2017 but has been increasing since (**Figure 5**).

The proportion of cattle with a PM-finding "liver fluke" decreased since 2018 (**Figure 6**). Post-mortem liver fluke findings are the result of both acute and past infections and a distinction could not be made from the data. Cattle from herds with a low milk production had a higher proportion of slaughtered cattle with a liver fluke finding (IRR = 1.27 for the 10% least producing herds). Herds located in central and western provinces had an increased risk of PM-finding "liver fluke" (IRR = 1.70–2.27).

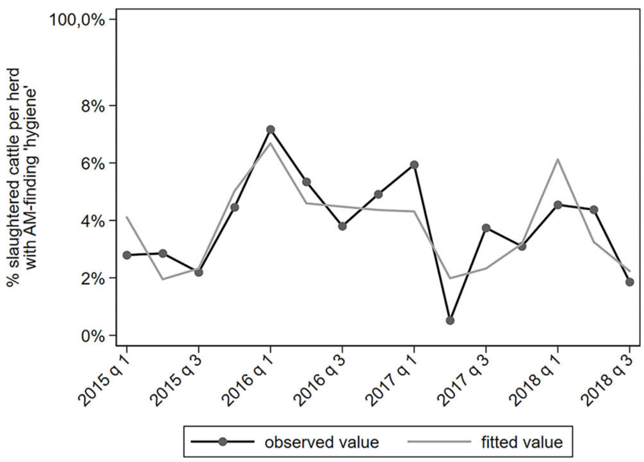


FIGURE 2 | Observed and predicted percentage of slaughtered cattle per dairy herd with a AM-finding categorized under "hygiene," per quarter between January 2015 to September 2018 ($N = 78,366$).

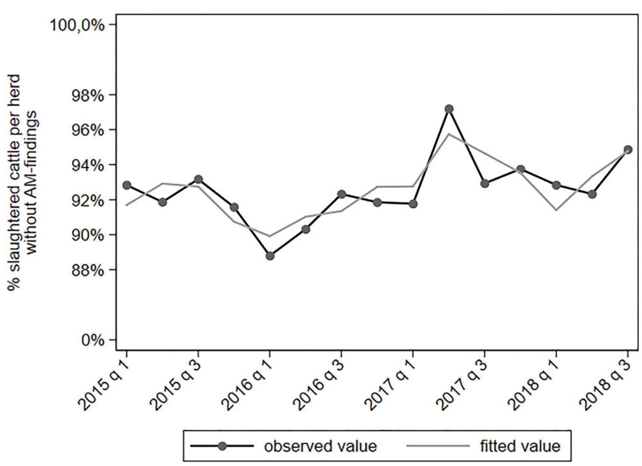


FIGURE 3 | Observed and predicted percentage of slaughtered cattle per dairy herd without AM-findings, per quarter between January 2015 to September 2018 ($N = 78,366$).

PM-findings classified as "lesions of the integumentary system" include lesions in the hock, hip, knee, shoulder, or front leg. The proportion of cattle with a PM-finding related to integumentary lesions increased in time since 2017q3 (**Figure 7**). Herds from the north of the Netherlands had a lower proportion of such findings than the average farm (IRR = 0.77). Herds from southern provinces had a higher proportion of such findings (IRR = 1.31–1.36).

PM-findings categorized as "round and buttock region" represent internal trauma and injuries in that part of the carcass. These can be caused in the herd of origin or during transport. The proportion of slaughtered cattle with such PM-findings fluctuated around 7% per herd per quarter (**Figure 8**). There were significant but no relevant associations with explanatory variables.

DISCUSSION

Meat inspection records of one large cattle slaughterhouse were analyzed in this study to evaluate the added value of slaughterhouse data for cattle health surveillance in the Netherlands. "Added value" was defined as health indicators that provide information regarding specific health problems, or new information not yet available in the TASC.

Representativeness of the Study Population

The characteristics of the dairy herds in the slaughterhouse data did not differ from the overall dairy cattle population. Therefore, the dairy herds in the slaughterhouse data were considered sufficiently representative for the Dutch dairy population. However, the distribution of the dairy herds in the slaughterhouse data was skewed toward the southern region, probably due to the location of the slaughterhouse in the south of the Netherlands.

Associations With Risk Factors

The model results revealed a number of noteworthy associations between farm of origin characteristics and the occurrence of meat inspection findings ("risk factors"). The objective of the TASC is to monitor trends and developments in cattle health, rather than case detection, yet the risk factors that were found may illustrate a profile of high-risk herds. This could lead to a more risk-based surveillance approach.

Carcasses of cows that originated from the 10% smallest dairy herds were less likely to be condemned than the sample mean, and carcasses that that originated from the 10% largest herds were more likely to be condemned. This is in agreement with a study by (5) on risk factors for whole carcass condemnation of slaughtered cattle in Switzerland. Also carcasses from the 10% smallest herds had less often a PM-finding related to the pulmonary membrane/peritoneum. One explanation for this could be that some of these findings are the result of infectious diseases which are less likely in smaller herds (8, 9).

PM-findings categorized under "liver fluke" were observed more often in the provinces N-Holland, Z-Holland, and Utrecht. These provinces are known as high-risk liver fluke areas in the Netherlands (10). Condemnation and PM-findings categorized under "integumentary" were observed less often in carcasses from cows that originated from the (northern) provinces with the farthest distance to the slaughterhouse (located in the south). This is somewhat surprising as it is suggested that injuries such as bruising might increase with the distance traveled by cattle (11). It is possible however that healthy cattle are transported over a longer distance than cattle that are less healthy, i.e., those are expected to be transported to a nearby slaughterhouse. Yet as a consequence, the association between farm of origin location and occurrence of certain PM-findings ("integumentary" and "condemnation")

TABLE 5 | Results of multivariable analyses of PM-findings amongst slaughtered cattle from dairy herds between January 1, 2015 and September 30, 2018, in incidence ratios (IRR) and 95% confidence intervals. Only associations with a p-value <0.05 that met the relevance criteria (IRR ≤0.8 or ≥1.25) are shown (N = 78,366).

PM-category	Condemnation	Lungs	Pulmonary membrane/ peritoneum	Heart	Liver fluke	Liver (ex. Liver fluke)	Kidneys	Udder	Integumentary	Round/ buttock	Gastrointestinal tract	No PM-findings
Explanatory variable	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**
Slaughter cow price (€/kg)	–	0.78 (0.69–0.88)	1.38 (1.25–1.52)	0.73 (0.60–0.89)	1.63 (1.39–1.90)	–	–	3.17 (2.79–3.60)	–	–	1.32 (1.04–1.68)	–
Milk production level at herd level (mean yearly net revenue; € per cow)												
Mean	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
10% lowest	–	–	–	–	1.27 (1.19–1.35)	–	–	–	–	–	–	–
40% lower	–	–	–	–	–	–	–	–	–	–	–	–
40% higher	–	–	–	–	–	–	–	–	–	–	–	–
10% highest	–	–	–	–	–	–	–	–	–	–	–	–
Missing	–	–	–	–	–	–	–	–	–	–	–	–
Herd size (mean number of cattle >2 years of age)												
Mean	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
10% smallest herds	0.74 (0.67–0.83)	–	0.80 (0.76–0.83)	–	–	–	–	–	–	–	–	–
40% smaller herds	–	–	–	–	–	–	–	–	–	–	–	–
10% larger herds	–	–	–	–	–	–	–	–	–	–	–	–
10% largest herds	1.26 (1.19–1.34)	–	–	–	–	–	–	–	–	–	–	–
Location of herd (province)												
Mean	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
Drenthe	0.79 (0.68–0.92)	–	–	–	0.70 (0.64–0.77)	–	–	–	–	–	–	–
Flevoland	–	–	–	–	–	–	–	–	–	–	–	-
Friesland	0.47 (0.40–0.54)	–	–	–	–	–	–	–	0.78 (0.74–0.83)	–	–	–
Gelderland	–	–	–	–	–	–	–	–	–	–	–	–
Groningen	0.66 (0.56–0.78)	–	–	–	0.72 (0.61–0.85)	–	–	–	–	–	–	–
Limburg	–	–	–	–	–	–	–	–	–	–	–	–
N-Brabant	1.38 (1.31–1.46)	–	–	–	0.67 (0.64–0.70)	–	–	–	1.27 (1.24–1.31)	–	–	–
N-Holland	1.26 (1.14–1.39)	–	–	–	1.97 (1.84–2.12)	–	–	–	–	–	–	–

(Continued)

TABLE 5 | Continued

PM-category	Condemnation	Lungs	Pulmonary membrane/ peritoneum	Heart	Liver fluke	Liver (ex. Liver fluke)	Kidneys	Udder	Integumentary	Round/ buttock	Gastrointestinal tract	No PM-findings
Explanatory variable	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**	**IRR**
Overijssel	–	–	–	–	0.73 (0.68–0.78)	–	–	–	–	–	–	–
Utrecht	1.50 (1.38–1.64)	–	–	–	1.70 (1.61–1.80)	–	–	–	–	–	–	–
Z-Holland	1.37 (1.26–1.48)	–	–	–	2.27 (2.16–2.38)	–	–	–	–	–	–	–
Zeeland	–	–	–	–	–	–	–	–	–	–	–	–

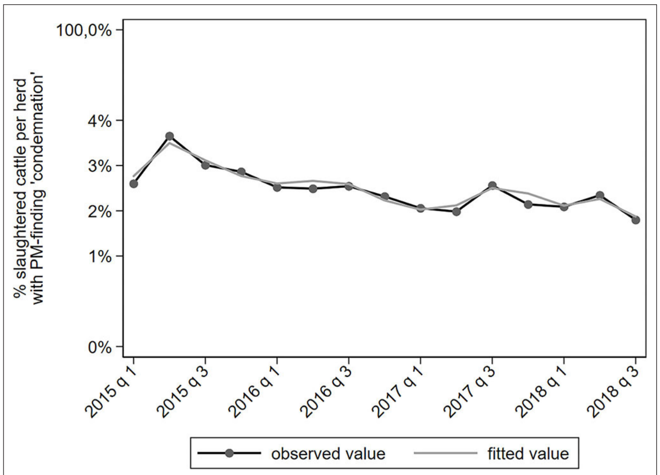


FIGURE 4 | Observed and predicted percentage of slaughtered cattle per dairy herd with a PM-finding categorized under "condemnation," per quarter between January 2015 to September 2018 ($N = 78{,}366$).

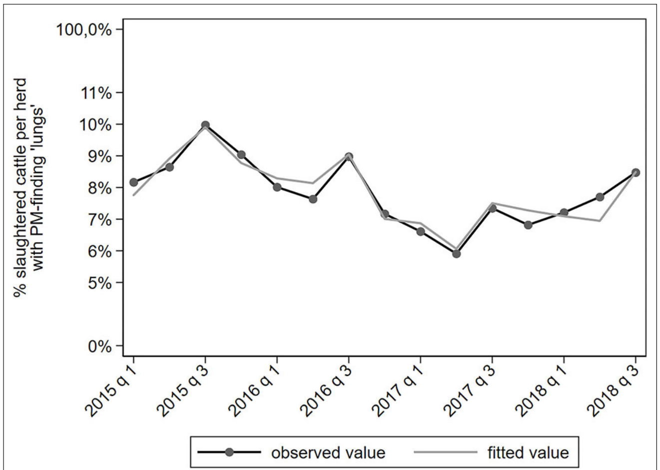


FIGURE 5 | Observed and predicted percentage of slaughtered cattle per dairy herd with a PM-finding categorized under "lungs," per quarter between January 2015 to September 2018 ($N = 78{,}366$).

were probably biased to some extent by the location of the slaughterhouse and should be interpreted with caution. Inclusion of meat inspection data from slaughterhouses in other regions is therefore of importance to assure sufficient regional coverage.

Slaughter prices vary constantly and are associated with live cattle prices and milk prices. For example, farmers are more driven to send cows to slaughter when milk prices are low, creating a greater supply of slaughter cows and consequently a decrease in slaughter cow price. This process is enhanced by changes in agricultural policy. During the study period, two major policy changes occurred in the Netherlands: (1) the abolishment of milk-quota in 2015 and (2) the introduction of the Phosphate Regulation in 2017. These events have

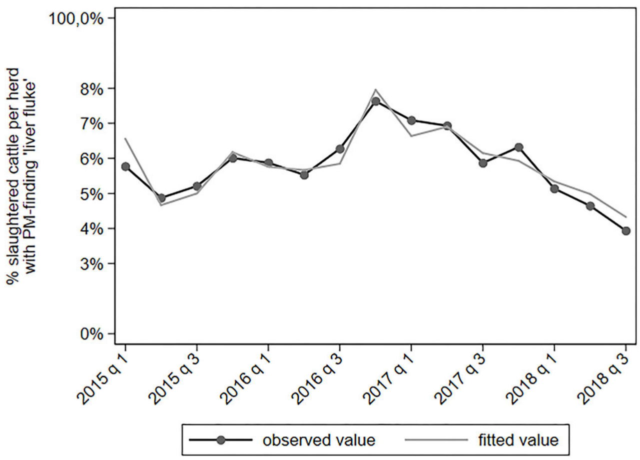


FIGURE 6 | Observed and predicted percentage of slaughtered cattle per dairy herd with a PM-finding categorized under "liver fluke," per quarter between January 2015 to September 2018 ($N = 78,366$).

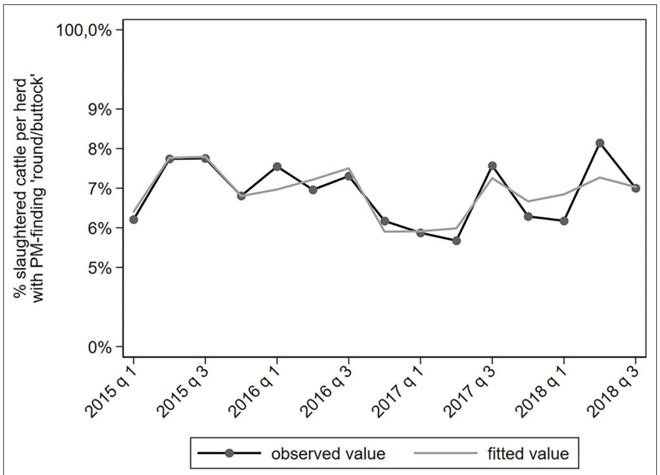


FIGURE 8 | Observed and predicted percentage of slaughtered cattle per dairy herd with a PM-finding categorized under "round/buttock region," per quarter between January 2015 to September 2018 ($N = 78,366$).

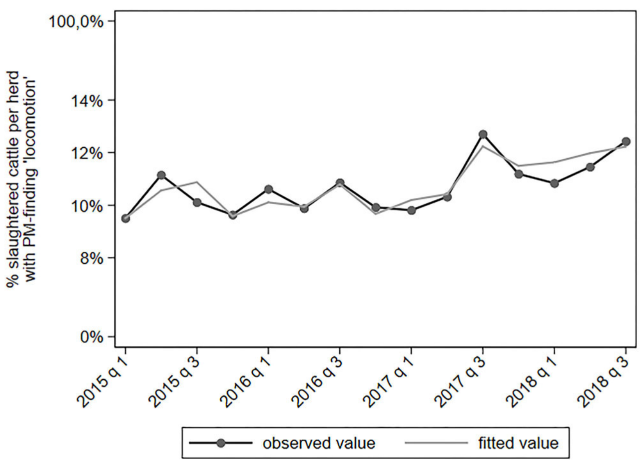


FIGURE 7 | Observed and predicted percentage of slaughtered cattle per dairy herd with a PM-finding categorized under "integumentary," per quarter between January 2015 to September 2018 ($N = 78,366$).

undoubtedly influenced farmer's culling decisions and possibly the health status of the slaughtered cattle population. In our study, slaughter cow price was included in the model as the mean national slaughter cow price per quarter of the year. The association between slaughter cow price and the probability of AM- and PM-findings was ambiguous, varying from an IRR of 0.73 to 3.57. This suggests that the quarterly slaughter cow prices did not capture the true relation between fluctuations in supply and demand of slaughter cows and their health status (expressed as the presence of AM- or PM-findings).

Finally, the model we used could not adequately describe the trend of some meat inspection findings, such as the AM-finding "hygiene." One reason for this could be that important explanatory variables are missing, such as type of farming system (conventional/organic) and whether or not grazing is applied. Unless this lack of fit is resolved, inadequately described meat inspection findings are unsuitable to be added to the TASC.

Trends of Meat Inspection Findings in Time

In this study, meat inspection records were translated into trends of the proportion of slaughtered cattle with AM- and/or PM-findings, resulting in meaningful indicators of cattle health. From the 16 categories analyzed, seven were deemed of added value to analyses in the existing trend analysis surveillance component. First, the PM-category "condemnation" is of relevance due to the severe character of this finding, although, there is a high diversity of possible reasons for carcass condemnation (12). The PM-categories "integumentary" and "round/buttock region" are relevant for cattle health surveillance as a welfare measure, which is not yet covered by the TASC. Thus, these results provide new information as such. The PM-categories "lungs" and "liver fluke" provide information regarding specific health problems such as respiratory disorders and fasciolosis. The proportion of cattle with a PM-finding "liver fluke" decreased since 2018 which is in agreement with a decrease in active liver fluke infections in dairy herds as a result of the dry summer of 2018 (unpublished data). The increasing trend in PM-findings categorized as "lungs" was unexpected however and is an example of an abnormal change that could be a reason for more in-depth investigation. Also, these results serve complementary to signals derived from other surveillance activities such as necropsy examinations of fallen stock. Finally, the categories "no AM-findings" and "no PM-findings" could serve as a potential favorable measure of animal health.

If meat inspection data were to be added to the existing TASC, results will be reported to a national steering committee on a quarterly basis, together with other indicators of cattle health that are part of the TASC (1). Possible causes of deviating trends may be investigated in more detail on request of the steering committee. An example of this process is the initiative to investigate reasons for the increased calf mortality in the Dutch dairy sector that was observed in 2009–2010, after a period of several years in which calf mortality rates remained stable (13). Another application of meat inspection data could be in the form of real-time spatiotemporal analyses, providing an opportunity for early-warning (syndromic) surveillance systems. This could be particularly interesting for diseases for which post-mortem lesions are more specific than clinical symptoms (12).

Challenges for Implementation

Slaughterhouse data could be a valuable source of information of herd types of which cattle health information is scarce, such as small-scale holders. Unfortunately, non-dairy herds were underrepresented in the dataset that was used for this study. This underlines the need for data from other slaughterhouses before implementation of meat inspection data analyses in the current surveillance system. However, the lack of standardization between slaughterhouses in recording of inspection findings presents challenges for implementation (14). In addition, although, official veterinarians and their auxiliaries are trained according to a standardized inspection protocol, the meat inspection remains a subjective judgement to some extent. Also, factors such as experience, motivation and dedication as well as local operational aspects impact the compliance with inspection protocols (15). As a result, diagnostic performance and inter-inspector variability are known challenges of meat inspection (15, 16) and bias apparent prevalences of meat inspection findings (17). It is expected however that this bias is rather constant over time, thus meaningful trends may still be derived from meat inspection data. Nevertheless, these issues need to be taken into account when using slaughterhouse data for cattle health surveillance.

CONCLUSION

Categorizing and analyzing routinely collected meat inspection data as herd-level frequencies of ante-mortem and post-mortem findings yields valuable cattle health indicators at population level. A number of indicators yields information that is not captured in other Dutch census data sources used in the national surveillance programme, or provides improved understanding when combined with signals from other surveillance components. Based on this study, stakeholders were advised to explore the availability of data from other slaughterhouses to improve the regional coverage and representation of various herd types to enable implementation of meat inspection data analyses in the cattle health surveillance system in the Netherlands.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: The datasets generated for this study will not be made publicly available as the data has been provided by a commercial abattoir, who wishes not to make their data publicly available. Requests to access these datasets should be directed to a.veldhuis@gdanimalhealth.com.

AUTHOR CONTRIBUTIONS

AV and GS developed the statistical models. AV performed the statistical analyses and wrote the first draft of the manuscript. All authors contributed to the conception and design of the study, interpretation of the results, manuscript revision, read, and approved the submitted version.

FUNDING

This study was commissioned by the Southern Agriculture and Horticulture Organization (ZLTO) and financed by DairyNL, the organization of the Dutch dairy supply chain.

ACKNOWLEDGMENTS

Correct interpretation of the slaughterhouse data was achieved through the valuable input of P. Jacobs (NVWA), D. Oorburg (Vion) and W. van Roessel (Vion), for which we are grateful.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.661459/full#supplementary-material

REFERENCES

1. Santman-Berends IMGA, Brouwer-Middelesch H, van Wuijckhuise L, de Bont-Smolenaars AJG, van Schaik G. Surveillance of cattle health in the Netherlands: monitoring trends and developments using routinely collected cattle census data. *Prev Vet Med*. (2016) 134:103–12. doi: 10.1016/j.prevetmed.2016.10.002
2. McKinley TJ, Lipschutz-Powell D, Mitchell AP, Wood JLN, Conlan AJK. Risk factors and variations in detection of new bovine tuberculosis breakdowns via slaughterhouse surveillance in Great Britain. *PLoS ONE*. (2018) 13:e0198760. doi: 10.1371/journal.pone.0198760
3. Dupuy C, Hendrikx P, Hardstaff J, Lindberg A. *Contribution of Meat Inspection to Animal Health Surveillance in Bovine Cattle*. EFSA Supporting Publications (2012). p. EN-322.
4. Dupuy C, Demont P, Ducrot C, Calavas D, Gay E. Factors associated with offal, partial and whole carcass condemnation in ten French cattle slaughterhouses. *Meat Sci*. (2014) 97:262–9. doi: 10.1016/j.meatsci.2014.02.008
5. Vial F, Schärrer S, Reist M. Risk factors for whole carcass condemnations in the Swiss slaughter cattle population. *PLoS ONE*. (2015) 10:0122717. doi: 10.1371/journal.pone.0122717

6. CBS Statistics Netherlands. *StatLine Data Portal.* (2021). Available online at: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/7123slac/table?ts=1610704274516 (accessed January 15, 2021).
7. Wageningen University and Research. *Agricultural Prices.* (2021). Available online at: https://www.agrimatie.nl/Prijzen.aspx?ID=15125 (accessed May 10, 2021).
8. Raaperi K, Nurmoja I, Orro T, Viltrop A. Seroepidemiology of bovine herpesvirus 1 (BHV1) infection among Estonian dairy herds and risk factors for the spread within herds. *Prev Vet Med*. (2010) 96:74–81. doi: 10.1016/j.prevetmed.2010.06.001
9. Broughan J, Judge J, Ely E, Delahay R, Wilson G, Clifton-Hadley R, et al. A review of risk factors for bovine tuberculosis infection in cattle in the UK and Ireland. *Epidemiol Infect*. (2016) 1:1–28. doi: 10.1017/S095026881600131X
10. Royal GD. *Liver Fluke* (in Dutch) (2021). Available online at: https://www.gddiergezondheid.nl/nl/Diergezondheid/Dierziekten/Leverbot (accessed May 10, 2021).
11. Strappini A, Metz J, Gallo C, Kemp B. Origin and assessment of bruises in beef cattle at slaughter. *Animal*. (2009) 3:728–36. doi: 10.1017/S1751731109004091
12. Dupuy C, Morignat E, Maugey X, Vinard JL, Hendrikx P, Ducrot C, et al. Defining syndromes using cattle meat inspection data for syndromic surveillance purposes: a statistical approach with the 2005-2010 data from ten French slaughterhouses. *BMC Vet Res*. (2013) 9:88. doi: 10.1186/1746-6148-9-88
13. Santman-Berends IMGA, Buddiger M, Smolenaars AJG, Steuten CDM, Roos CAJ, van Erp AJM, et al. A multidisciplinary approach to determine factors associated with calf rearing practices and calf mortality in dairy herds. Prev Vet Med. (2014) 117:375–87. doi: 10.1016/j.prevetmed.2014.07.011
14. Vial F, Reist M. Comparison of whole carcass condemnation and partial carcass condemnation data for integration in a national syndromic surveillance system: the Swiss experience. *Meat Sci*. (2015) 101:48–55. doi: 10.1016/j.meatsci.2014.11.002
15. Stärk KDC, Alonso S, Dadios N, Dupuy C, Ellerbroek L, Georgiev M, et al. Strengths and weaknesses of meat inspection as a contribution to animal health and welfare surveillance. *Food Control*. (2014) 39:154–62. doi: 10.1016/j.foodcont.2013.11.009
16. Arzoomand N, Vågsholm I, Niskanen R, Johansson A, Comin A. Flexible distribution of tasks in meat inspection – a pilot study. *Food Control*. (2019) 102:166–72. doi: 10.1016/j.foodcont.2019.03.010
17. Enøe C, Christensen G, Andersen S, Willeberg P. The need for built-in validation of surveillance data so that changes in diagnostic performance of post-mortem meat inspection can be detected. *Prev Vet Med*. (2003) 57:117–25. doi: 10.1016/S0167-5877(02)00229-5

Conflict of Interest: AV, DS, HW, and GS are employed by company Royal GD. MB is employed by company Vion.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 16 July 2021
doi: 10.3389/fvets.2021.647711

Exploiting Scanning Surveillance Data to Inform Future Strategies for the Control of Endemic Diseases: The Example of Sheep Scab

Eilidh Geddes[1,2], Sibylle Mohr[3], Elizabeth Sian Mitchell[4], Sara Robertson[5], Anna M. Brzozowska[5], Stewart T. G. Burgess[2] and Valentina Busin[1]*

[1] School of Veterinary Medicine, University of Glasgow, Glasgow, United Kingdom, [2] Moredun Research Institute, Pentlands Science Park, Edinburgh, United Kingdom, [3] Boyd Orr Centre for Population and Ecosystem Health, College of Medical, Veterinary and Life Sciences, University of Glasgow, Glasgow, United Kingdom, [4] Carmarthen Veterinary Investigation Centre, Animal and Plant Health Agency, Carmarthen, United Kingdom, [5] Surveillance Intelligence Unit, Animal and Plant Health Agency, Weybridge, United Kingdom

OPEN ACCESS

Edited by:
Chris J. M. Bartels,
Animal Health Works, Netherlands

Reviewed by:
Alan Radford,
University of Liverpool,
United Kingdom
Fernanda Dorea,
National Veterinary Institute, Sweden

***Correspondence:**
Eilidh Geddes
Eilidh.Geddes@moredun.ac.uk

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics,
a section of the journal Frontiers in Veterinary Science

Received: 30 December 2020
Accepted: 15 June 2021
Published: 16 July 2021

Citation:
Geddes E, Mohr S, Mitchell ES, Robertson S, Brzozowska AM, Burgess STG and Busin V (2021) Exploiting Scanning Surveillance Data to Inform Future Strategies for the Control of Endemic Diseases: The Example of Sheep Scab. Front. Vet. Sci. 8:647711. doi: 10.3389/fvets.2021.647711

Scanning surveillance facilitates the monitoring of many endemic diseases of livestock in Great Britain, including sheep scab, an ectoparasitic disease of major welfare and economic burden. There is, however, a drive to improve the cost-effectiveness of animal health surveillance, for example by thoroughly exploiting existing data sources. By analysing the Veterinary Investigation Diagnosis Analysis (VIDA) database, this study aimed to enhance the use of existing scanning surveillance data for sheep scab to identify current trends, highlighting geographical "hotspots" for targeted disease control measures, and identifying a denominator to aid the interpretation of the diagnostic count data. Furthermore, this study collated and assessed the impact of past targeted disease control initiatives using a temporal aberration detection algorithm, the Farrington algorithm, to provide an evidence base towards developing cost-effective disease control strategies. A total of 2,401 positive skin scrapes were recorded from 2003 to 2018. A statistically significant decline in the number of positive skin scrapes diagnosed ($p < 0.001$) occurred across the study period, and significant clustering was observed in Wales, with a maximum of 47 positive scrapes in Ceredigion in 2007. Scheduled ectoparasite tests was also identified as a potential denominator for the interpretation of positive scrapes by stakeholders. Across the study period, 11 national disease control initiatives occurred: four in Wales, three in England, and four in Scotland. The majority ($n = 8$) offered free diagnostic testing while the remainder involved knowledge transfer either combined with free testing or skills training and the introduction of the Sheep Scab (Scotland) Order 2010. The Farrington algorithm raised 20 alarms of which 11 occurred within a period of free testing in Wales and one following the introduction of the Sheep Scab (Scotland) Order 2010. In summary, our analysis of the VIDA database has greatly enhanced our knowledge of sheep scab in Great Britain, firstly by identifying areas for targeted action and secondly by offering a framework to measure the impact of future disease control initiatives. Importantly this framework could be applied to inform future strategies for the control of other endemic diseases.

Keywords: surveillance, sheep scab, diagnostic data, existing data, disease control initiatives, data analysis, temporal aberration detection algorithm

INTRODUCTION

Endemic diseases, though widely accepted in modern livestock farming, pose a significant challenge to livestock health, welfare, and productivity with often serious consequences for public health and food security (1, 2). However, the increased exploitation of existing data sources for animal health surveillance presents a significant opportunity to monitor populations and to develop new strategies for the control of endemic diseases. Scanning surveillance is the term used in Great Britain (GB) to refer to the laboratory-based monitoring of disease trends from voluntary diagnostic submissions originating from a variety of sources, similar to passive surveillance (3, 4). This represents a cost-effective methodology for monitoring a variety of diseases, particularly endemic diseases. Scanning surveillance in GB is predominantly achieved through the Veterinary Investigation Diagnosis Analysis (VIDA) database, which is a collection of all clinical diagnoses made from submissions to the Animal and Plant Health Agency's (APHA's) Veterinary Investigation Centres (VICs), Scotland's Rural College Veterinary Services' (SRUC VS) Disease Surveillance Centres (DSCs), and partner post-mortem examination providers for livestock and wildlife in GB (5). Increasingly, the potential to further the use of existing surveillance data sources is being recognised (2, 6). As such, GB's surveillance strategies are changing and encouraging the exploitation of existing data to complement the introduction of new data sources and develop a more complete picture of endemic diseases of livestock (1, 2, 4).

Sheep scab is an ectoparasitic disease caused by infestation of the skin/fleece with the mite, *Psoroptes ovis* (7). It is an endemic disease of particular economic importance to the sheep industry, costing an estimated £78–202 million per year (8). *P. ovis* is an obligate ectoparasite which abrades the skin of the sheep and, in the clinical phase of infestation, causes extreme pruritus (9, 10). Prolonged infestations can result in hypoproteinaemia from albumin loss, causing ill-thrift and emaciation (11). In GB various actions, including statutory control programmes, have been implemented to achieve eradication (12), yet at present the national farm-level prevalence is estimated to be around 9% (13, 14). As the picture of sheep scab has previously shown a high regional variation in prevalence (12, 14), areas with a high disease burden need to be identified to better focus efforts and resources for disease control. An important concept for monitoring the true prevalence of a disease also includes knowing the proportion of disease within the population at risk. However, utilising diagnostic datasets from the voluntary submission of samples by farmers seeking a diagnosis through their veterinarian such as the VIDA database often lacks appropriate denominator (animal population) data, which can be a limitation for their interpretation by veterinarians and other stakeholders (15).

Many approaches have been trialled in an attempt to control endemic diseases due to their complexity. For sheep scab, since the removal of the statutory control programme in place until 1992 (12), a number of targeted disease control initiatives have been adopted to improve the awareness and knowledge of the disease and to contribute towards control. These initiatives are normally industry- or government funded, run for a limited period of time, and are working towards a set goal such as increasing awareness, providing education or advice on treatment options (16). However, initiatives are often expensive, time consuming, and difficult to coordinate. Therefore, developing techniques to measure the impact of such initiatives could provide guidance on their use as part of a more sustainable and cost-effective approach to control.

To aid in the evaluation of past targeted disease control initiatives and guide their future use, a temporal aberration detection algorithm (TADA) could be employed. TADAs are a model conventionally used as a bio-surveillance tool to detect outbreaks of pathogens in hospital settings (17). The application of a TADA can identify a statistically significant increase in the number of cases over time, from a baseline period which is free from outbreaks. An alarm is raised when the count exceeds the threshold calculated by the TADA, indicating a potential outbreak (18–20). However, the sensitivity and specificity of the model need to be carefully balanced so not to generate an excessive number of false-positive alarms whilst still reliably identifying true outbreaks. The TADA has the potential to offer a real-time evaluation of disease, making them a very important tool within public health. Now, their application for other purposes is also being increasingly acknowledged, particularly within veterinary medicine (6, 21).

Through analysis of the sheep scab diagnostic data held in the VIDA database, this study aimed to further exploit this existing surveillance data to (i) identify current trends, (ii) highlight geographical "hotspots" suitable for targeted disease control measures and (iii) identify a denominator from the VIDA database itself to contextualise the trends of the diagnostic count data for stakeholders. Finally, this study collated and assessed the impact of past targeted disease control initiatives using a TADA in order to provide an evidence base towards developing cost-effective disease control strategies.

MATERIALS AND METHODS

VIDA Data Collection

The VIDA database records all diagnostic submissions made to the APHA's VICs, SRUC VS's DSCs, and partner post-mortem examination providers for livestock and wildlife in GB. Samples are routinely submitted on a voluntary basis from referring private veterinarians and farmers for diagnostic investigations. The submissions can include one or multiple samples containing a variety of sample material (from whole carcases to blood, milk, or faecal samples). When a diagnosis (or multiple diagnoses) is made by a Veterinary Investigation Officer (VIO), the submission is assigned one (or multiple) VIDA codes. VIDA codes are assigned to submissions where the diagnosis meets pre-determined and defined criteria.

For sheep scab, the VIDA database includes diagnoses made by the APHA or SRUC at VICs and DSCs through a standardised and United Kingdom Accreditation Service (UKAS) accredited skin scrape test to directly identify the *P.ovis* mites from skin scrape samples. Skin scrape samples are taken using a scalpel blade on the outside edge of a lesion site by a private veterinarian and are subsequently examined by laboratory staff at the VIC or

DSC. Samples are examined under direct microscopy or using a potassium hydroxide digest if the initial microscopy did not detect any ectoparasites (22). In some cases, sheep scab can also be diagnosed from the identification of mites from other sample types such as wool plucks or hair. If a positive sheep scab diagnosis is reached for at least one sample within a submission (of any sample type), the submission is assigned the diagnostic code "390". For the purposes of this study all submissions that were assigned the diagnostic code "390" (herein referred to as "positive scrapes") were extracted from the VIDA database, together with their submission date and a regional geolocator (approximating county-level), from January 1995 to September 2019 inclusive. However, due to incompleteness of the data in early years, the foot-and-mouth disease epidemic in 2001 and the subsequent restocking of livestock in 2002 as a result of the outbreak, only data from January 2003 onwards were included in the analysis.

Since denominators such as total sheep population were not easily accessible for use in this study and would not be continuously available to contextualise the count of positive scrapes, alternative denominators were sought from the VIDA database itself. Therefore, two further datasets were extracted from the VIDA database: *total diagnostic submissions* from ovines and the *scheduled ectoparasite tests* from ovine submissions. The *total diagnostic submissions* dataset represents the count of all diagnostic ovine submissions submitted to the APHA, SRUC VS and partner post-mortem providers. These samples could contain any type of sample material (e.g., carcass, blood, faeces, etc.) from an ovine submission. Where multiple samples (of any type) were included within one submission, this was regarded as a single submission. The *scheduled ectoparasite tests* dataset represents the count of the number of ectoparasite tests for ovine submissions scheduled by the VIO. The tests included: the APHA's test code "TC0081" for an ectoparasite examination and the SRUC VS test codes "MicrSk" for microscopic examination of the skin or hair, "Shscab" for sheep scab examination, and "Skpara" for microscopic examination for lice or mites. Where multiple skin scrapes were scheduled for one submission, this was recorded as one scheduled scrape. Both datasets were extracted as a total count per year for the 16-year study period (2003–2018).

Sheep Scab Initiatives

To identify and collate the details of all targeted sheep scab control initiatives which took place during the study period across Great Britain (GB), a variety of sources were consulted. Primarily, information regarding the initiatives was retrieved from publicly available sources such as peer-reviewed literature, government and industry reports (23–25). Experts from industry and government were also consulted to capture initiatives where there was insufficient to no information otherwise available. National initiatives, i.e., those which took place in one or more of the three countries in GB, were selected as they were designed to reach a larger portion of the population at risk, featured well-defined start and end dates, and had a higher degree of information available from primary sources. All of the initiatives identified were categorised into a "type" pertaining to the planned actions of the initiative to allow grouping of initiatives. These categories were: "free testing", where the cost of skin scraping tests was waived or subsidised; "knowledge transfer & skills training", where education was provided through workshops and training sessions; "knowledge transfer & free testing", where education was provided, coupled with free skin scraping tests; and "legislation", where new legislation was introduced beyond the scope of the Sheep Scab Order (1997) which was in place prior to the beginning of the study period.

Descriptive Data Analysis

All analyses and visualisations, unless otherwise stated, were conducted using the statistical programming language R version 4.0.0 (26). Positive scrape submissions where the regional geolocator was missing ($n = 91$) were excluded from analyses requiring this information.

Temporal Analysis

The total number of positive scrapes were grouped by year and country (i.e., England, Scotland, and Wales) to assess the temporal pattern of sheep scab across GB. A Poisson regression was then applied to test the effect of year on the total number of yearly positive scrapes.

The total counts of the two potential denominator datasets were directly compared to the number of positive scrapes for the 16-year study period (2003–2018) to estimate their suitability as denominators. The most appropriate potential denominator dataset for the interpretation of trends by stakeholders was subsequently visualised as counts per year alongside the count of positive scrapes.

Spatial Analysis

The positive scrape data were provided with a pre-defined regional geolocator, approximate to county-level, which was used to descriptively assess the spatial distribution of sheep scab across GB. The counts were aggregated by region, (i) firstly per year for the full study period and then (ii) totalled across all years. The aggregated totals were mapped using a shapefile provided by the APHA, including the correct boundaries of the regions defined in the dataset. In addition, the location of the DSCs and VICs were determined and plotted by extracting longitude and latitude from their postcodes using the Office for National Statistics (ONS) Postcode Lookup database (27).

Aberration Detection

The (original) Farrington algorithm was applied to measure the impact of disease control initiatives on the number of positive scrapes recorded in the VIDA database. As the sheep scab initiatives were specific to each country within GB, a separate time series analysis was performed for each country. The Farrington algorithm, which uses an over-dispersed quasi-Poisson regression-based method for weekly aberration detection was applied to the number of positive scrapes per country, aggregated by week in accordance with the ISO 8601 international standard of time and date (28). This was applied using the "surveillance" package in R version 1.18.0 (18, 20, 29). Note that besides the original Farrington method other algorithms were considered and trialled, among them the improved Farrington (30), CUSUM, and negative binomial method (19). Even so, the original Farrington proved to be a suitable algorithm for the particular challenges of this type of surveillance data, such as adjusting for any unknown past outbreaks, not requiring a long baseline period, and the ability to account for any seasonal effect in the data if present (as sheep scab is well established as a highly seasonal disease) (12, 31). In addition, the original Farrington method has been previously (and successfully) applied to other data extracts from the VIDA database (15).

To determine a baseline period for training the model, weekly aggregates for each country were visualised as time series to ensure the baseline period was free of suspected aberrations or disease control initiatives. The threshold was set at 0.01 level of uncertainty to increase the likelihood of detecting only true aberrations as submissions could have been influenced by a number of further factors beyond disease control initiatives. In addition to this, each data series were decomposed into seasonal, trend, and residual components, visually inspected, and seasonality either confirmed or rejected using a Kruskall Wallis test (p-values considered statistically significant if $p < 0.05$) (32, 33).

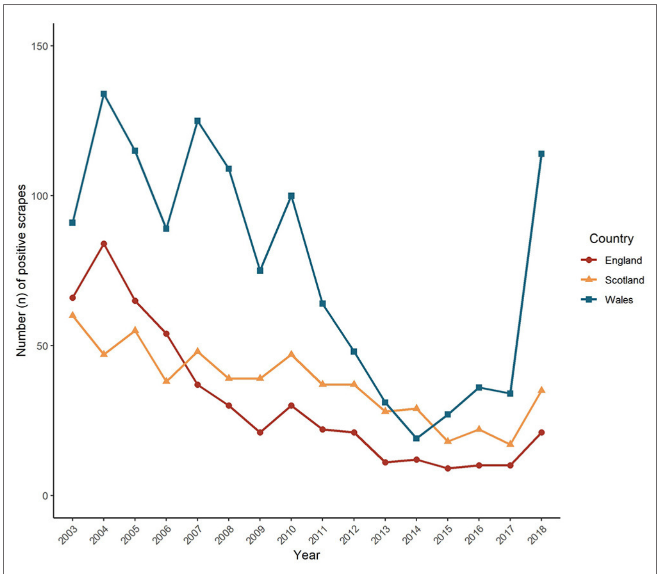


FIGURE 1 | Annual trend of VIDA positive scrapes (sheep scab diagnoses) per country for GB ($n = 2{,}310$) from 2003 to 2018.

RESULTS

Descriptive Analysis

A total of 2,401 positive scrapes were recorded between the 1st January 2003 and 31st December 2018. A significant decrease was observed in the annual count of positive scrapes from the beginning of the study period ($p < 0.001$). The maximum number of positive scrapes was recorded in 2004 ($n = 277$), and the lowest in 2015 ($n = 55$). In contrast to the overall decline observed over the study period, the number of positive scrapes increased by over 2.5 times from 2017 ($n = 68$) to 2018 ($n = 172$). Of the total count of positive scrapes, 2,310 included a geolocator from which the country information could be derived. The annual pattern of positive scrapes per country is displayed in **Figure 1**. Overall England, Wales and Scotland presented a similar pattern, with a prolonged but fluctuating decline over the study period, with the exception of a sharp increase in counts in Wales in 2018. Wales exhibited consistently higher counts of positive scrapes compared to England and Scotland, with the highest count in 2004 ($n = 134$). The only year where the number of positive scrapes was higher in Scotland ($n = 29$) than in Wales ($n = 19$) was in 2014. In England, the highest count of positive scrapes was also observed in 2004 ($n = 84$), and after a consistent decline, the lowest count occurred in 2015 ($n = 9$). In Scotland, the highest number of positive scrapes was in 2003 ($n = 60$), and the lowest in 2017 ($n = 17$).

Of the two datasets extracted from the VIDA database as potential denominators, the total *scheduled ectoparasite tests* dataset had a count of 5,171 over the 16-year period. Of this, the count of positive scrapes for sheep scab represented 46.4% of the total *scheduled ectoparasite tests*, and this dataset also exhibited a similar temporal trend to the number of positive scrapes per year, as shown in **Figure 2**. The total diagnostic submissions dataset had a count of 146,199 submissions, representing a very small proportion (1.6%) of the number of positive scrapes (and as such, was not visualised here).

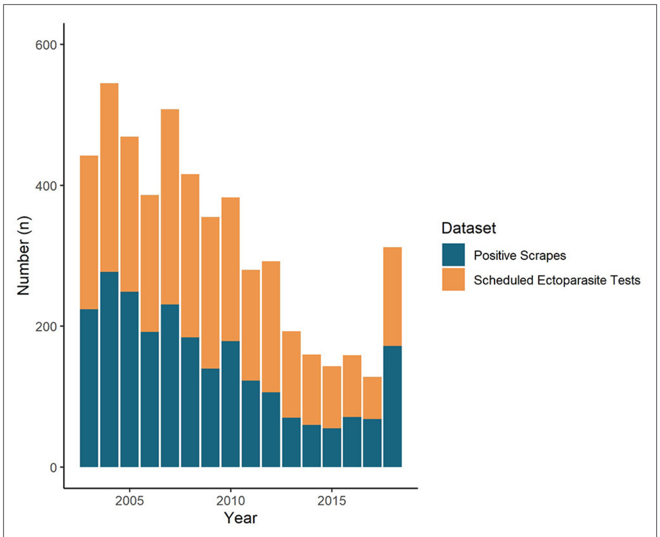


FIGURE 2 | Annual trend of the number of scheduled ectoparasite tests ($n = 5{,}171$) and VIDA positive scrapes for GB from 2003 to 2018 ($n = 2{,}401$).

Descriptive Spatial Analysis

In total, 2,310 of the 2,401 positive scrapes (96.2%) included a regional geolocator (approximating county-level) which allowed them to be categorised into 69 defined geographical regions across GB (seven in Wales, 14 in Scotland, and 48 in England). At the beginning of the study period, 25 VICs were in operation across GB. As of the end of 2018, 18 were still operational. All

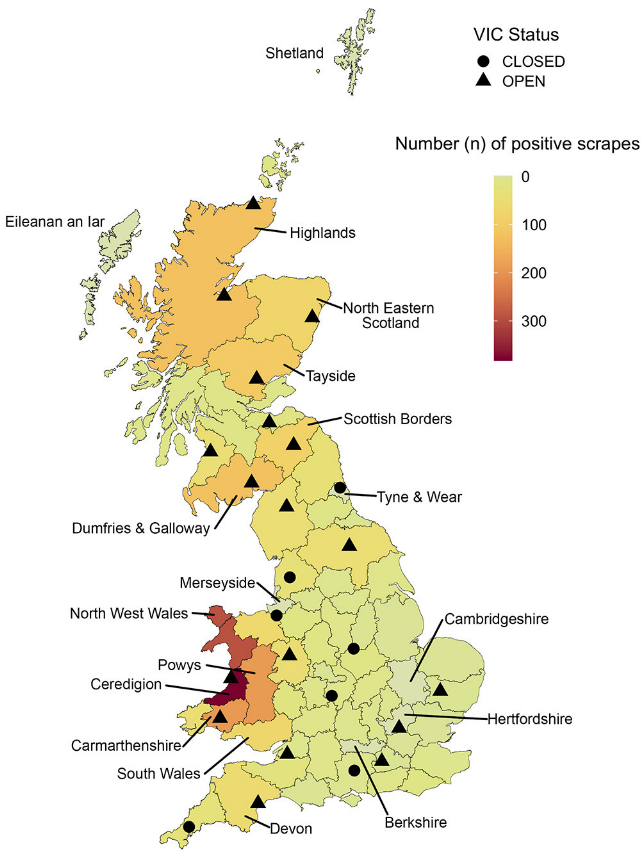


FIGURE 3 | Spatial distribution of the total VIDA positive scrapes (sheep scab diagnoses) from 2003-2018. Points overlaying this represent the DSCs and VICs that were open during the study period. The shape of the point, a circle of triangle, represents the centre's status as of 2020: closed or open, respectively. Labels identify the names of key regions mentioned in text and **Table 1**.

closures during the study period took place in England, with one closure in 2013, and the other six in 2014 (**Figure 3**).

The number of positive scrapes across GB was unevenly distributed, with 52.4% of positive scrapes originating from Wales, 25.8% from Scotland and 21.8% from England. The county with the highest number of positive scrapes across all years was Ceredigion, representing 16.4% of the total diagnoses (**Table 1**). Ceredigion also represented the focal point within Wales, with the adjacent North West Wales, Powys, and Carmarthenshire also displaying high counts as seen in **Table 1**. Of the 7 Welsh regions, five were within the 10 regions with the highest total positive scrapes, while the remaining five regions were all in Scotland (**Table 1**). In England, the region with the most positive scrapes was Devon with 52. Regions with zero positive scrapes within the study period were Berkshire, Cambridgeshire, Hertfordshire, Merseyside, Tyne & Wear, Eileanan an Iar, and Shetland.

From the study period (i.e. 2003–2018), 4 years (2003, 2007, 2013, and 2018) were selected to represent the spatial distribution of positive scrapes. These years were selected to represent the first

TABLE 1 | The ten regions with the highest totals of VIDA positive scrapes (sheep scab diagnoses) for GB across 2003–2018.

Region	Country	Number of positive scrapes	Percentage of the total number of positive scrapes (%)
Ceredigion	Wales	378	16.4%
North West Wales	Wales	279	12.1%
Carmarthenshire	Wales	189	8.2%
Powys	Wales	188	8.1%
Highlands	Scotland	121	5.2%
Dumfries & Galloway	Scotland	120	5.2%
Tayside	Scotland	103	4.5%
Scottish Borders	Scotland	82	3.5%
North Eastern Scotland	Scotland	75	3.2%
South Wales	Wales	68	2.9%

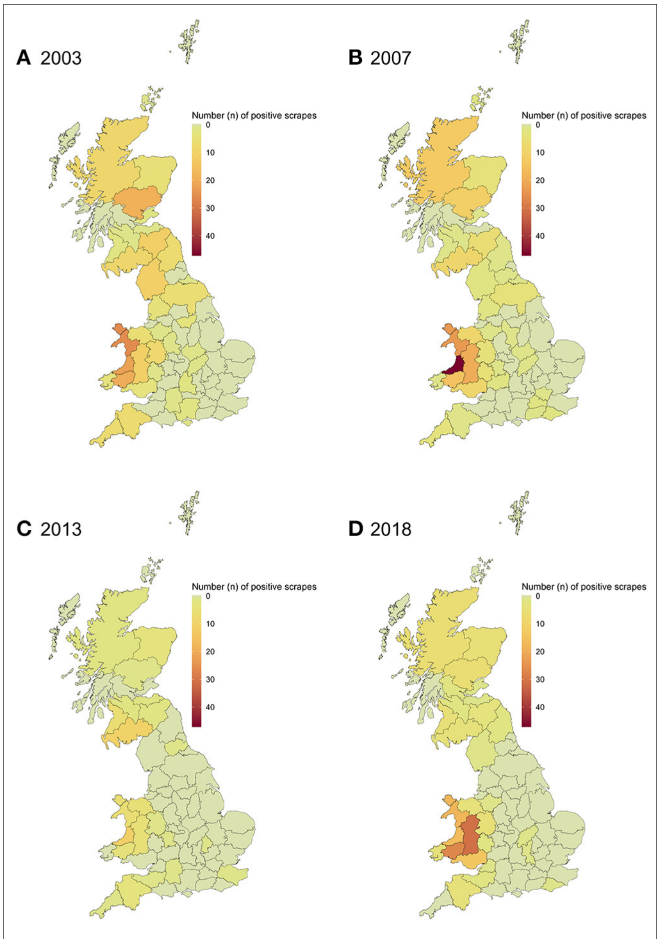


FIGURE 4 | Spatial distribution of VIDA positive scrapes in GB for four key years in the 2003–2018 study period: **(A)** 2003, **(B)** 2007, **(C)** 2013, and **(D)** 2018.

and last years of the study period, with the interim years spaced between these years whilst illustrating particular changes in the distribution over time (**Figure 4**). The count of positive scrapes in 2003 (**Figure 4A**) saw a maximum of 26 positive scrapes in one region, North West Wales. Overall, the highest number of positives scrapes was seen across the west of Wales, which included Ceredigion, Carmarthenshire and North West Wales ($n = 20–26$) and in Tayside, Scotland ($n = 11$). In 2007 (**Figure 4B**), Ceredigion observed the highest number of positive scrapes seen in one county across all years, with a total of 47. This peak in Ceredigion also aligned with a more generalised increase in positive scrapes within Wales during 2007 (mean of 17.8 positive scrapes per region). The count in England and Scotland remained low ($n = <14$). In 2013 (**Figure 4C**), a decrease in the number of positive scrapes occurred across the country, with a maximum of 11 positive scrapes in any region, observed in Ceredigion. In 2018, the low counts ($n = <7$) remained across England and Scotland (**Figure 4D**); however, counts in Wales varied from 4 in North East Wales to 27 in Carmarthenshire.

Sheep Scab Initiatives

Within the study period, 11 targeted sheep scab disease control initiatives, as described in **Table 2**, took place between 2003 and 2018 across GB: 4 in Wales, three in England and four in Scotland.

Wales

In Wales, all four initiatives were categorised as "free testing". The details of the first APHA free testing initiative (operating from 1st December 2003 to 28th February 2004), the Hybu Cig Cymru (HCC)/Meat Promotion Wales and the sheep scab ELISA validation free testing were all similarly sourced from personal correspondence (**Table 2**). As such, no official report was available on the results of these initiatives. However, a report was available for the second period of APHA free testing (from 20th December 2017 to 31st March 2018) (38) which outlined the intended aims and results of this initiative (**Table 2**).

England

England shared two of its three initiatives with Wales: the APHA free testing (from 1st December 2003 to 28th February 2004), and the sheep scab ELISA validation free testing. The third, instead, was an industry-led "knowledge transfer & skills training" initiative named "Stamp out Scab", which operated for 15 months and was funded by the Rural Development Programme for England (RDPE). The details of the two initiatives shared with Wales were similarly obtained from personal correspondence (**Table 2**). Information about the aims and workshops delivered to veterinarians and Registered Animal Medicines Advisors (RAMAs) as part of the "Stamp out Scab" campaign was obtained from the advertising material and previous literature (**Table 3**).

Scotland

Uniquely, Scotland offered its initiatives continuously throughout the study period. For the first 8 months SRUC offered free diagnostic testing for sheep scab, similar to the APHA free testing initiatives. Then, the Scottish Sheep Scab Initiative (SSSI) was introduced as a result of industry pressure to control the disease. This was led by industry and government through the Scottish Sheep Scab Industry Working Group, offering advice on best practise coupled with free testing to increase awareness of sheep scab (**Table 2**). After the SSSI ended, the SRUC free testing resumed and a working group was formed to pave the way towards developing legislation, the Sheep Scab (Scotland) Order 2010. This reintroduced sheep scab as a notifiable disease in Scotland, mandating the reporting of suspected cases (35, 37).

Aberration Detection

The Farrington algorithm was applied separately for each country due to the devolved nature of animal health in GB, which has been shown to apply to sheep scab through the largely devolved initiatives (**Table 2**), and differences in counts and trends for each country (**Figure 1**). Regarding the time series composition, visual inspection of the results suggested that a seasonal effect was present for Wales and Scotland but not for England, which was statistically confirmed through Kruskal-Wallis tests (Wales: $p = 0.004$; Scotland: $p = 0.007$; England: $p = 0.230$) (**Supplementary Figure 1**). For all countries, the highest number of counts occurred across autumn and winter while counts in the summer months remained low (**Supplementary Figure 1**).

In Wales, the period of APHA free testing was also excluded from the baseline period, as it was for England. Due to a higher number of counts per week in Wales as opposed to England and Scotland (**Supplementary Figure 2**) convergence of the model was achieved with a shorter baseline period of 2.5 years, from week 27 of 2004 to the end of 2006. Therefore, the Farrington algorithm was applied across week 1 of 2007 to the end of 2018. This allowed the Farrington algorithm to evaluate three of the four initiatives that occurred across the study period.

The Farrington algorithm for Wales raised 15 alarms (**Figure 5A**) from 2017 to 2018. In total, 11 of the 15 alarms (73.3%) occurred from December 2017 to March 2018, falling within the APHA free testing initiative period. The other four alarms did not align with any other known national initiatives. The counts observed on weeks with alarms, compared to the upper threshold produced by the model are displayed in **Table 3**. The highest number of positive scrapes occurring in 1 week was 16, on the week beginning 15th January 2018. Also, with the exception of two alarms, all alarms occurred in either winter or spring (**Table 3**).

The baseline period used for England ran from week 1 of 2006 to week 52 of 2009. A later starting reference period was used due to high counts being observed at the beginning of the study period compared with later years (**Supplementary Figure 2B**), and also taking into consideration the APHA period of free testing from 1st December 2003 to the 28th February 2004 (**Figure 5B**). Therefore, the study period analysed by the Farrington algorithm was from week 1 of 2010 to week 52 of 2018. The Farrington algorithm raised one alarm during the study period. The alarm was raised in week 39 of 2010 (week beginning 27th September), when 4 positive scrapes were diagnosed, exceeding the upper boundary of 3.45 predicted positive scrapes (**Table 3**) and also representing the highest count

TABLE 2 | Description of the targeted national sheep scab disease control initiatives occurring between the 1st January 2003 and 31st December 2018 in GB.

Initiative name/organisation	Start date	End date	Initiative type	Description
Wales				
APHA*	01-12-2003	28-02-2004	Free testing	Period of free skin scrape testing funded and operated by the APHA, operated across England and Wales (*S Mitchell, personal communication).*
HCC/ Meat Promotion Wales	01-01-2007	28-02-2007	Free testing	Period of free skin scrape testing funded by HCC, an industry-led levy board (*S Mitchell, personal communication).*
Sheep scab ELISA validation	01-04-2015	01-09-2015	Free testing	Period of free testing to encourage submission of a skin scrape and blood sample to the APHA to validate the sheep scab ELISA. (*S Mitchell, personal communication).*
APHA	20-12-2017	31-08-2018	Free testing	Period of free testing funded by the Welsh Government and operated by the APHA, after the first reported cases of resistance to macrocyclic lactones were identified (34).
England				
APHA*	01-12-2003	28-02-2004	Free testing	Period of free skin scrape testing funded and operated by the APHA *(S Mitchell, personal communication).*
Stamp out Scab	01-01-2013	31-03-2014	Knowledge transfer & skills training	Initiative aimed at knowledge transfer (facilitated by RAMAs for dissemination to clients) and skills training (sessions provided by ADAS veterinarians), instigated by the AHDB and funded through the RDPE (24, 25).
Sheep scab ELISA validation	01-04-2015	01-05-2015	Free testing	Period of free testing initiated by the APHA inviting the submission of a skin scraping and blood sample for the validation of the sheep scab ELISA. (*S Mitchell, personal communication).*
Scotland				
SRUC VS*	01-01-2003	10-09-2003	Free testing	Period of free skin scrape testing funded and operated by the SRUC (35).
Scottish Sheep Scab Initiative*	11-09-2003	31-12-2006	Knowledge transfer & free testing	A largely industry-led, 3-year long initiative launched at Kelso ram sales initiated by NFU Scotland (36), towards increasing awareness of sheep scab and promoting best practise in disease control through the provision of information (23).
SRUC VS	01-01-2007	16-12-2010	Free testing	Period of free skin scrape testing funded and operated by the SRUC (35).
Sheep scab (Scotland) Order 2010	17-12-2010	Ongoing†	Legislation	Mandated the notification of holdings with or suspected to have sheep scab to the local APHA office (37).

**Initiatives which occurred within the study period but were not included in the analysis.*
†*As of September 2020.*

of the weekly time-series for England. This alarm occurred outside the time period of any of the regional initiatives.

Scotland offered initiatives throughout the study period, hence including these in the baseline period was unavoidable. However, the baseline period was adapted to minimise any initial effect from the start of the SSSI. The baseline used was the 4-year period from week 1 of 2005 to the end of 2008, therefore allowing for analysis using the Farrington algorithm from the start of 2009 to the end of 2018 (**Supplementary Figure 2C**). The Farrington algorithm yielded four alarms, two in 2010, one in 2015 and one in 2016 (**Figure 5C**). Of the two alarms raised in 2010, the second was raised in week 51, beginning the 20th December, the week after the introduction of the Sheep Scab (Scotland) Order 2010.

DISCUSSION

As with many endemic diseases in GB, sheep scab will not be eradicated without considerable effort and long-term commitment from all stakeholders, requiring a high level of investment. This is further complicated by the highly variable prevalence of this disease throughout the country. Therefore,

TABLE 3 | Alarms raised by the Farrington algorithm applied to England, Wales and Scotland.

Country	Alarm date		Count of positive scrapes	Upper threshold
	Year	Week		
England	2010	39	4	3.45
Wales	2008	26	4	3.83
	2015	51	5	3.75
	2016	52	5	3.78
	2017	51	8	4.24
	2017	52	9	4.24
	2018	2	12	4.96
	2018	3	16	4.44
	2018	5	7	3.63
	2018	6	4	3.36
	2018	7	5	3.37
	2018	8	6	3.37
	2018	9	5	3.65
	2018	10	4	3.14
	2018	11	4	2.34
	2018	38	3	2.67
Scotland	2010	10	3	2.96
	2010	51	6	5.35
	2015	53	3	2.64
	2016	51	5	4.07

Periods monitored: England 2010-2018; Wales 2007-2018; Scotland 2009-2018. Week is the week number in accordance with the ISO:8601 standard. The upper threshold is the number of counts, as determined by the Farrington algorithm, which would need to be exceeded before an alarm is generated.

the development of targeted, sustainable and cost-effective strategies is paramount to the future success of disease control interventions. In this study, one of the aims was to investigate an existing data source for the scanning surveillance of sheep scab in GB (the VIDA database) to identify current trends and geographical "hotspots" for sheep scab. The analysis confirmed that the spatial distribution of positive scrapes displayed a pattern comparable to previous studies, with high counts observed in Wales, northern Scotland, and northern England. This suggests that prioritising these areas for targeted control strategies could lead to maximum impact. In contrast to previous studies which have found that sheep scab prevalence is either stable or increasing in GB (13, 14, 39), the diagnostic count data analysed here showed a decline in annual counts of positive scrapes for all countries of GB, with the exception of 2018.

Due to the nature of voluntarily submitted diagnostic data, the decline in the count of positive scrapes may reflect a true decrease in sheep scab over the study period, but was likely influenced by many additional factors which need to be considered, including fewer confirmatory diagnoses being sought by veterinarians and farmers. Repeat outbreaks are likely for sheep scab (14), and for flocks where the disease has been diagnosed before, farmers may opt to treat subsequent outbreaks without seeking another confirmatory diagnosis, leading to these outbreaks not being recorded in the VIDA database. A further explanation is that the reduction in submissions for diagnostic sampling may also be influenced by the costs, which currently stand at £24.70 per ectoparasite screen excluding any veterinary costs in England and Wales (40). This is a particular concern for flocks with small profit margins (41, 42). Conversely, in Scotland the submission of ectoparasite screens for cases of suspected sheep scab has been free since 2002 (35). Given that the highest number of positive scrapes originated from Wales and free submissions from Scotland are not substantially higher, it seems unlikely that the decision to submit samples for testing is purely driven by financial factors. It should also be considered that sheep scab is a disease with a large social component due to the associated stigma of having and reporting a sheep scab infestation (which also has negative consequences in Scotland, with movement restrictions being applied). Consequently, there may be little incentive to submit samples, particularly in Scotland. In addition to this, fewer confirmatory diagnostics using the skin scraping methodology may be sought due to (i) veterinary practises using in-house testing, (ii) the closure of some VICs in England and Wales in 2013 and 2014 (43), and (iii) the development and commercialisation of the new diagnostic sheep scab ELISA (44) in early 2017. As the results from in-house testing or diagnostics performed using the sheep scab ELISA are run by commercial companies, they are currently not freely available to support veterinary surveillance.

Somewhat unexpected after the sustained annual decline was the substantial increase in positive scrapes in Wales in 2018, to 3.5 times the counts of the previous year. This substantial increase could raise concern of a true increase in disease prevalence within the country. However, this also corresponded with the APHA free testing initiative in Wales from December 2017 to March 2018 (**Table 2**), which saw a 500% increase in submissions (38) and likely drives this effect. Although an increase in positive scrapes in 2018 was also seen in England and Scotland, which were not taking part in the initiative, the magnitude was considerably smaller and the effect of the Welsh initiative on disease awareness at national level could not be excluded (38). One of the objectives of our analysis was specifically to identify disease trends and, coupled with the aberration detection analysis of disease control initiatives, identify possible explanations for the apparent increase or decrease in positive scrapes. While a true increase in sheep scab in 2018 cannot be excluded, the free testing initiative has undoubtedly driven the increase in submission and, as a consequence, the number of positive scrapes. To ascertain whether this substantial increase in cases was predominantly due to the offer of free testing, follow up analysis of subsequent years should be carried out.

The "hotspots" (areas with high numbers of confirmed cases) identified in the VIDA data were similar to previous studies, with high counts occurring in Wales and northern Scotland (12, 14). This supports the use of the VIDA database as a suitable means of scanning surveillance, providing a continuous and evidence-based source of information to target areas for disease control initiatives. With further refinement of the geolocators, for example to a county-parish level, the spatial

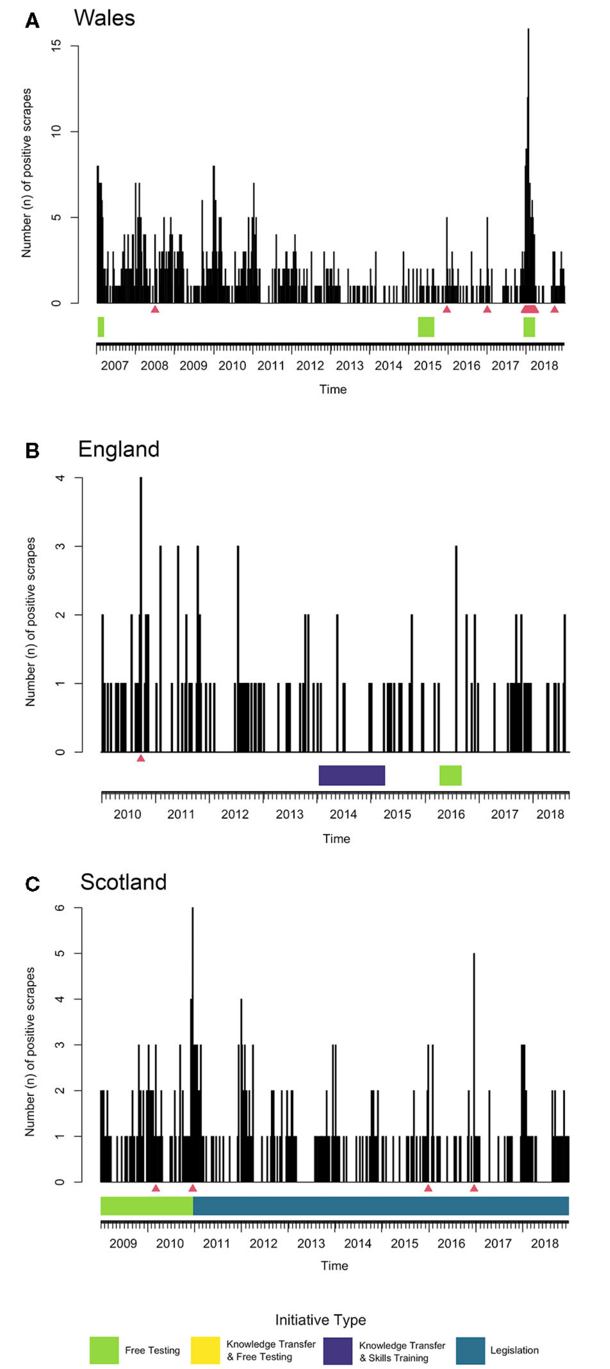


FIGURE 5 | Time-series plot with the Farrington algorithm applied to the count of VIDA positive scrapes in: **(A)** Wales from week 1 of 2007 to the end of 2018, using a reference period of week 27 of 2004 to the end of 2006; **(B)** England from week 1 of 2010 to the end of 2018, using a reference period of week 1 of 2006 to the end of 2009; **(C)** Scotland from the beginning of 2009 to the end of 2018, using a reference period from the beginning of 2005 to the end of 2008. Red triangles indicate alarms raised by the TADA, showing a significant deviation from the expected count. The coloured horizontal bars are a visual representation of targeted sheep scab disease control initiatives in place in that country. These include free testing (green), knowledge transfer & free testing (yellow), knowledge transfer & skills training (purple), and legislation (blue). For description of initiatives see **Table 2**.

distribution of positive scrapes would allow for more localised control programmes.

As positive scrape submissions recorded in the VIDA database are likely to present only a subset of sheep scab outbreaks, it cannot be used on its own to derive true disease prevalence. Submission might be influenced by factors such as geographical location, awareness of the disease, economic values (of both the disease and the animals), the density of animals in an area, and the number of animals affected (5). To account for the spatial distribution of sheep scab in relation to the sheep population a denominator such as total sheep population from the yearly June agricultural census (45) or density of sheep per holding could be applied to the positive scrapes. These denominators could help highlight additional "hotspot" areas where the sheep population might be small, but many animals are infested. In this study, for example, eight regions (six in England and two in Scotland) had zero positive scrape diagnoses between 2003 and 2018. Some of these areas may be highly industrialised with low density sheep populations, which could explain the lack of sheep scab diagnoses, but in others, it could represent a low presence of disease. As mentioned previously, geographical locations can also have a significant impact on the submission of diagnostic samples. In the case of Eileanan an Iar (the Western Isles off the north west coast of Scotland), since the introduction of the Sheep Scab (Scotland) Order 2010, the Scottish Government reported 32 sheep scab notifications in this region between 2010 and 2019 (46), yet no positive scrapes were recorded in the VIDA database. This suggests that diagnoses have either not been pursued or are made in a different way (e.g., through private veterinarians). It is, however, important to highlight that these are very different datasets; with the Scottish Government notification data recording suspected cases, and the VIDA database representing confirmed positive diagnoses. However, from both databases it is clear that sheep scab is likely vastly underreported in GB, which may be at least in part due to the historic but still present stigma towards the disease among the farming community.

It is important for stakeholders, such as veterinarians, to have an awareness of the overall trends in diagnoses being made when interpreting the positive scrape data to understand external factors which may have influenced the overall submission rate, such as the VIC closures in 2013 and 2014. The total diagnostic submissions dataset offered an insight into the number of diagnostic submissions made across the SRUC VS and the APHA. However, due to the number of other unrelated diagnoses which are included in the VIDA database, positive scrapes represented a very small proportion of this dataset and would not be a very valuable denominator for stakeholders to interpret trends beyond providing supplementary context on how the VIDA database is being used. The *scheduled ectoparasite tests* dataset, which included all diagnostic tests conducted to reach a diagnosis where an ectoparasitic disease is suspected by the submitting veterinarian or VIO, would likely be a more useful denominator obtained from the VIDA database for stakeholders as it could estimate the likelihood of sheep scab from all cases of suspected ectoparasitic disease. This dataset demonstrated that almost half (46%) of the total *scheduled ectoparasite tests* were positive.

This highlights the importance of sheep scab in the context of ectoparasitic diseases and demonstrates just how often it is the causative disease when a diagnosis is sought. By analysing the dataset for other VIDA codes, further insight into other ectoparasites (i.e., lice) as differential diagnoses for sheep scab could also be investigated.

The second aim of this study was to investigate the impact of past disease control initiatives and provide recommendations for their future application. The information about the sheep scab control initiatives described here were only available through the organisation(s) that coordinated them, or from personal correspondence. With the exception of results from the APHA free testing from December 2017 to March 2018 being published in a quarterly disease surveillance report (47) and a survey measuring the impact of the SSSI (23), information on the outcome of the majority of initiatives was unavailable. This makes it impossible to determine whether these initiatives were successful without first-hand experience. It was also difficult to locate information pertaining to the operational dates or original objectives of the initiatives as sources were not available publicly. This study has highlighted that there is considerable value in retaining details about these events in the public domain, not only to avoid specific knowledge being only available to the coordinating organisations (and often only to a few people) but also to avoid this knowledge being lost or forgotten. Therefore, to facilitate a more effective approach to information storage about sheep scab control initiatives, it may be beneficial to consider instating a GB-wide database, similar to the USA's centres for Disease Control and Prevention (CDC) list of national health initiatives, which cover a range of diseases important to human health (48). If used prospectively a database could encourage support from other stakeholders, and ultimately offer a more cost-effective alternative by increasing the impact of each individual disease control programme.

The impact of the initiatives was measured using the Farrington algorithm, a TADA commonly used to detect outbreaks of pathogens in healthcare settings (17). Limited previous work has been conducted to investigate the impact of different types of disease control initiatives (23), but the application of the Farrington algorithm could offer a near real-time evaluation. However, the performance of each TADA is highly reliant on the quality of the baseline period supplied. This was very much variable for each country due to conflicts with initiatives and high counts at the beginning of the study period which prevented model convergence, notably for England (**Supplementary Figure 2B**). In addition, it is possible that aberrations occurred during the baseline which were not known, thus could not be accounted for.

The most common initiatives for targeted sheep scab control were based on free testing and accounted for 8 out of 11 initiatives. The majority of resulting aberrations aligned with the APHA free testing from December 2017 to March 2018 in Wales, which indicates that free testing provoked an increase in diagnostic submissions, achieving one of the main goals of this type of initiative and thus disclosed more disease. Compared to the other types of disease control initiatives shown here, free testing initiatives are much easier to implement and coordinate and, above all, offer a cost-effective way to increase testing at a specific point in time. Yet, more often, only long-term education through knowledge transfer or knowledge exchange can produce lasting changes in mindset and behaviour (49) that could ultimately decrease the incidence of sheep scab. Therefore, there may be potential benefits in combining free testing and knowledge exchange initiatives in future. However, as shown, the impact of knowledge transfer activities is more difficult to quantify. No aberrations specifically aligned with initiatives such as "Stamp out Scab", a knowledge transfer & skills training initiative. This was likely due to the aim of this initiative not being to directly impact the number of submissions, but to increase the overall awareness of the disease instead. As such, to effectively measure the impact of knowledge transfer initiatives, alternative methods should be sought.

Scotland was in a unique position with initiatives in place throughout the full study period. Therefore, the baseline period had to be set within the SSSI, which likely meant a higher baseline than would have been optimal. Despite this, alarms were still generated: one at the introduction of the new legislation and a further two within the notifiable period suggesting the alarms generated may be representative of true aberrations. Furthermore, this may represent that the notifiable status which was implemented in 2010 has successfully increased the disclosure of sheep scab cases within Scotland.

To summarise, the impact of free testing and legislation initiatives could be measured with the aberration detection analysis as the initiatives caused an increase in positive scrapes. The further use of this method is therefore promising for the application to other endemic diseases and takes into consideration a number of factors including prevalence, awareness, economic burden, and current disease control methods.

In conclusion, the further analysis of an existing scanning surveillance source, the VIDA database, enhanced our knowledge of sheep scab by identifying potential "hotspot" areas for targeted disease control initiatives. It shows a decline in overall submissions, and confirmed that Wales in particular is an area to focus on for future control efforts. Furthermore, scheduled *ectoparasite tests* was proposed as a denominator for stakeholders to interpret the raw number of positive scrapes. Finally, the application of a Farrington algorithm offered a framework to objectively measure the impact of targeted disease control initiatives, something that is being advocated widely as a more cost-effective and sustainable approach to the long-term control of endemic diseases and as a complementary tool in scanning surveillance.

DATA AVAILABILITY STATEMENT

The data analysed in this study is subject to the following licences/restrictions. Data were obtained from a third party source, the Animal and Plant Health Agency (APHA). Requests to access these datasets should be directed to corresponding author for forwarding to the appropriate contact.

AUTHOR CONTRIBUTIONS

EG performed the analysis and wrote the manuscript. VB and SM contributed to the study design, assisted with the analysis, and in writing the manuscript. EM, SR, and AB provided the data for analysis, assisted with the interpretation of the results, and contributed to the manuscript. SB contributed to the study design and contributed to the manuscript. All authors reviewed the final manuscript.

FUNDING

This work was funded by the UK Veterinary Medicines Directorate (VMD) under project VM0545. SB and SM were further supported by the Scottish Government's Rural Affairs Food and Environment Strategic Research (RESAS) programme [SM as part of the Centre of Expertise on Animal Disease Outbreaks (EPIC)].

ACKNOWLEDGMENTS

The authors gratefully acknowledge the data provided by the Animal and Plant Health Agency (APHA) and Scotland's Rural College (SRUC) for this study, and also would like to thank Philip Jones for reviewing the manuscript before submission. The work presented has been adapted from work submitted as part of a Master's thesis by EG.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.647711/full#supplementary-material

REFERENCES

1. Scottish Government T. *The Review of Veterinary Surveillance*. (2011) Available online at: www.scotland.gov.uk
2. UK Surveillance Forum [UKSF]. *The UK approach to animal health surveillance*. (2019) Available online at: http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/oremailPSI@nationalarchives.gsi.gov.uk
3. Irvine RM. A conceptual study of value chain analysis as a tool for assessing a veterinary surveillance system for poultry in Great Britain. *Agric Syst.* (2015) 135:143–58. doi: 10.1016/j.agsy.2014.12.007
4. Hoinville LJ, Alban L, Drewe JA, Gibbens JC, Gustafson L, Häsler B, et al. Proposed terms and concepts for describing and evaluating animal-health surveillance systems. *Prev Vet Med.* (2013) 112:1–12. doi: 10.1016/j.prevetmed.2013.06.006
5. APHA. Veterinary Investigation Diagnosis Analysis (VIDA). (2019) Available online at: http://apha.defra.gov.uk/vet-gateway/surveillance/scanning/vida.htm
6. Dórea FC, Sanchez J, Revie CW. Veterinary syndromic surveillance: current initiatives and potential for development. *Prev Vet Med.* (2011) 101:1–17. doi: 10.1016/j.prevetmed.2011.05.004
7. Kirkwood AC. History, biology and control of sheep scab. *Parasitol Today.* (1986) 2:302–7. doi: 10.1016/0169-4758(86)90124-9
8. Nixon EJ, Wall R, Vineer HR, Stubbings L. The high cost of sheep scab. *Vet Rec.* (2020) 187:325.1–325. doi: 10.1136/vr.m3888
9. Berriatua E, French NP, Broster CE, Morgan KL, Wall R. Effect of infestation with Psoroptes ovis on the nocturnal rubbing and lying behaviour of housed sheep. *Appl Anim Behav Sci.* (2001) 71:43–55. doi: 10.1016/S0168-1591(00)00166-0
10. Corke MJ, Broom DM. The behaviour of sheep with sheep scab, Psoroptes ovis infestation. *Vet Parasitol.* (1999) 83:291–300. doi: 10.1016/S0304-4017(99)00065-5
11. Sargison ND, Busin V. A model for the control of psoroptic mange in sheep. *Vet Rec.* (2014) 175:481–3. doi: 10.1136/vr.g6810
12. French NP, Berriatua E, Wall R, Smith K, Morgan KL. Sheep scab outbreaks in Great Britain between 1973 and 1992: spatial and temporal patterns. *Vet Parasitol.* (1999) 83:187–200. doi: 10.1016/S0304-4017(99)00057-6
13. Bisdorff B, Milnes A, Wall R. Prevalence and regional distribution of scab, lice and blowfly strike in Great Britain. *Vet Rec.* (2006) 158:749–52. doi: 10.1136/vr.158.22.749
14. Rose H, Learmount J, Taylor M, Wall R. Mapping risk foci for endemic sheep scab. *Vet Parasitol.* (2009) 165:112–8. doi: 10.1016/j.vetpar.2009.06.037
15. Tongue SC, Eze JI, Correia-Gomes C, Brülisauer F, Gunn GJ. Improving the utility of voluntary ovine fallen stock collection and laboratory diagnostic submission data for animal health surveillance purposes: a development cycle. *Front Vet Sci.* (2020) 6:487. doi: 10.3389/fvets.2019.00487
16. Department of Agriculture Food and the Marine. *National Farmed Animal Health Strategy 2017–2022: A framework for collective action by stakeholders*. (2017). Available online at: https://fdocuments.net/embed/v1/national-farmed-animal-health-strategy-2-022-national-farmed-animal-health-strategy.html
17. Yuan M, Boston-Fisher N, Luo Y, Verma A, Buckeridge DL, A. systematic review of aberration detection algorithms used in public health surveillance. *J Biomed Inform.* (2019) 94:103181–103181. doi: 10.1016/j.jbi.2019.103181
18. Höhle M, Mazick A. "Aberration Detection in R Illustrated by Danish Mortality Monitoring,". In: T. Kass-Hout, X. Zhang, editors. *Biosurveillance: A Health Protection Priority* (London: CRC Press) (2010), 215–38.
19. Salmon M, Schumacher D, Höhle M. Monitoring count time series in R: aberration detection in public health surveillance. *J Stat Softw.* (2016) 70:10. doi: 10.18637/jss.v070.i10
20. Zhou H, Burkom H, Winston CA, Dey A, Ajani U. Practical comparison of aberration detection algorithms for biosurveillance systems. *J Biomed Inform.* (2015) 57:446–55. doi: 10.1016/j.jbi.2015.08.023
21. Dórea FC, Vial F. Animal health syndromic surveillance: a systematic literature review of the progress in the last 5 years (2011–2016). *Vet Med Res Rep.* (2016) 7:157–70. doi: 10.2147/VMRR.S90182
22. Ministry of Agriculture Fisheries and Food. *Manual of Veterinary Parasitological Lab Techniques*. Ref book 418. Ministry of Agriculture, Fisheries and Food (1971).
23. ADAS. An Evidence Base for New Legislation and Guidance for Implementation of a Compulsory Treatment Period for Sheep Scab. (2008).
24. Phillips K, Webb D, Fuller H, Brown C, Lovatt F. Help needed to stamp out sheep scab. *Vet Rec.* (2013) 172:510–510. doi: 10.1136/vr.f2959
25. ADAS. Stamp Out Scab - Training and awareness campaign. (2013). Available online at: www.waterendfarm.co.uk
26. R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria (2020). Available online at: https://www.R-project.org/
27. Office for National Statistics. *National Statistics Postcode Lookup (November 2019).* (2019) Available online at: https://geoportal.statistics.gov.uk/datasets/national-statistics-postcode-lookup-november-2019
28. International Organization for Standardization. ISO 8601:2004. (2004) Available online at: https://www.iso.org/iso-8601-date-and-time-format.html
29. Farrington CP, Andrews NJ, Beale AD, Catchpole MA. A statistical algorithm for the early detection of outbreaks of infectious disease. *J R Stat Soc Ser A Stat Soc.* (1996) 159:547. doi: 10.2307/2983331
30. Noufaily A, Enki D, Farrington P, Garthwaite P, Andrews N, Charlett A. An improved algorithm for outbreak detection in multiple surveillance systems. (2012) Available online at: http://ojphi.org
31. Kirkwood AC. Some observations on the biology and control of the sheep scab mite Psoroptes ovis (hering) in Britain. *Vet Parasitol.* (1985) 18:269–79. doi: 10.1016/0304-4017(85)90053-6

32. Hyndman RJ, Khandakar Y. Automatic time series forecasting: the forecast package for R. *J Stat Softw.* (2008) 27:1–22. doi: 10.18637/jss.v027.i03
33. Kruskal WH, Wallis WA. Use of ranks in one-criterion variance analysis. *J Am Stat Assoc.* (1952) 47:583–621. doi: 10.1080/01621459.1952.10483441
34. Doherty E, Burgess S, Mitchell S, Wall R. First evidence of resistance to macrocyclic lactones in Psoroptes ovis sheep scab mites in the UK. *Vet Rec.* (2018) 182:106–106. doi: 10.1136/vr.104657
35. Blissitt M, Rigby M, Hosie M. *Ongoing battle against sheep scab: history and progress*. (2012). Available online at: https://www.vettimes.co.uk/app/uploads/wp-post-to-pdf-enhanced-cache/1/ongoing-battle-against-sheep-scab-history-and-progress.pdf
36. Hosie B. *The Scottish Sheep Scab Initiative*. (2005). Available online at: http://r1.ufrrj.br/adivaldofonseca/wp-content/uploads/2014/06/ectoparasite-workshop05.pdf
37. The Scottish Government. The Sheep Scab (Scotland) Order 2010. (2010). asp 418.
38. APHA. Report into free ectoparasite examination for sheep in Wales. (2018). Available online at: http://apha.defra.gov.uk/documents/surveillance/diseases/ectoparasite-report-1217-0318.pdf
39. Chivers C-A, Rose Vinner H, Wall R. The prevalence and distribution of sheep scab in Wales: a farmer questionnaire survey. *Med Vet Entomol.* (2018) 32:244–50. doi: 10.1111/mve.12290
40. APHA. Disease surveillance tests - parasitology. (2020). Available online at: https://science.vla.gov.uk/Tests/PDF/DST_PdfPriceList.pdf
41. Harvey D, Scott C. *Farm Business Survey 2018/19 - Hill Farming in England*. (2020). Available online at: http://www.ncl.ac.uk/nes/business/agriculture/survey/#farmbenchmarkingservice
42. Quality Meat Scotland [QMS]. *Cattle and Sheep Enterprise Profitability in Scotland*. (2017). Available online at: https://www.qmscotland.co.uk/sites/default/files/cattle_and_sheep_enterprise_profitability_in_scotland_2017.pdf
43. Anon. AHVLA confirms rationalisation of laboratory services. *Vet Rec.* (2011) 169:348–348. doi: 10.1136/vr.d6173
44. Burgess ST, Innocent G, Nunn F, Frew D, Kenyon F, Nisbet AJ, et al. The use of a Psoroptes ovis serodiagnostic test for the analysis of a natural outbreak of sheep scab. *Parasit Vectors.* (2012) 5:7. doi: 10.1186/1756-3305-5-7
45. National Statistics. June Agricultural Census: June 2019. (2019) Available online at: https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2019/10/final-results-june-2019-agricultural-census/documents/june-agricultural-census-2019/june-agricultural-census-2019/govscot%3Adocument/june-agricultural-census-2019.pdf
46. APHA. *Sheep scab notifications 2010–2019.* (2020). Available online at: https://www.gov.scot/binaries/content/documents/govscot/publications/transparency-data/2019/05/sheep-scab-notifications/documents/sheep-scab-notifications-2010-2019/sheep-scab-notifications-2010-2019/govscot%3Adocument/Sheep%2Bscab%2Bnotifications%2B2010-2019.pdf
47. APHA. *GB small ruminant quarterly report Disease surveillance and emerging threats Volume 21 Q2 April-June 2018.* (2018). Available online at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/738915/pub-survrep-sr0418.pdf
48. CDC. *National Health Initiatives, Strategies, and Action Plans*. (2020) Available online at: https://www.cdc.gov/publichealthgateway/strategy/index.html
49. 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 footrot. *Prev Vet Med.* (2017) 139:123–33. doi: 10.1016/j.prevetmed.2016.05.009

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.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 06 August 2021
doi: 10.3389/fvets.2021.660857

U.S. Cattle Producer Adoption of Secure Beef Supply Plan Enhanced Biosecurity Practices and Foot-and-Mouth Disease Preparedness

Christopher C. Pudenz[1]*, James L. Mitchell[2], Lee L. Schulz[1] and Glynn T. Tonsor[3]

[1] Department of Economics, Iowa State University, Ames, IA, United States, [2] Department of Agricultural Economics and Agribusiness, University of Arkansas, Fayetteville, AR, United States, [3] Department of Agricultural Economics, Kansas State University, Manhattan, KS, United States

OPEN ACCESS

Edited by:
Jonathan Rushton,
University of Liverpool,
United Kingdom

Reviewed by:
Wendy Beauvais,
Purdue University, United States
Nick Lyons,
European Commission for the Control of Foot and Mouth Disease (EuFMD), Italy

***Correspondence:**
Christopher C. Pudenz
ccpudenz@iastate.edu

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics,
a section of the journal Frontiers in Veterinary Science

Received: 29 January 2021
Accepted: 02 June 2021
Published: 06 August 2021

Citation:
Pudenz CC, Mitchell JL, Schulz LL and Tonsor GT (2021) U.S. Cattle Producer Adoption of Secure Beef Supply Plan Enhanced Biosecurity Practices and Foot-and-Mouth Disease Preparedness. Front. Vet. Sci. 8:660857. doi: 10.3389/fvets.2021.660857

The prospect of a foot-and-mouth disease (FMD) outbreak in U.S. livestock populations has motivated the development of the Secure Beef Supply (SBS) Plan, which includes a comprehensive list of enhanced biosecurity practices that aim to prevent FMD transmission and facilitate continuity of business during an outbreak. While FMD poses a serious threat to livestock production in the United States, little is known about producers' uptake of the enhanced biosecurity practices included in the SBS Plan. In this study, we benchmark adoption and feasibility-of-adoption perceptions for U.S. cattle producers. Our results show adoption of the 13 enhanced biosecurity practices is generally low. Especially concerning is the low adoption of the three strongly-recommended pre-outbreak practices—having a biosecurity manager, having a written operation-specific enhanced biosecurity plan, and having a line of separation. Adoption of the pre-outbreak practices is likely low because the benefits of adopting the practices depend on a low probability, uncertain event. That said, producers who have adopted the pre-outbreak practices are more likely to have higher feasibility ratings for the remaining enhanced biosecurity practices, suggesting that adoption of the strongly recommended practices is associated with adoption of all enhanced biosecurity during an FMD outbreak. Complementarity is examined and shows that adoption of the pre-outbreak practices coincides with adoption of the outbreak-specific practices. Taken together, our results suggest that adoption of the strongly recommended pre-outbreak practices could help facilitate a quicker and more effective U.S. cattle industry response to an FMD outbreak in the United States.

Keywords: biosecurity, cattle, disease, FMD, Secure Beef Supply

INTRODUCTION

Increased international travel and trade raises the likelihood of foreign animal disease introduction into the United States. Not everyone in the U.S. agriculture industry, however, is necessarily aware of the risks posed by foreign animal diseases. According to a National Animal Health Monitoring System cow-calf study, only 32.5% of operations claim to be fairly knowledgeable about foot-and-mouth disease (FMD) (1). As a majority of operations are not knowledgeable about FMD, it is not surprising that only 10.4% of cow-calf operations strongly agree that the United States is prepared to handle an outbreak of an animal disease not presently found in the United States (1). While actual preparedness may be better than perceived by producers, and technologies and tools continue to evolve in the preparedness and response toolkit, the lack of confidence in the United States' ability to respond to a disease like FMD is concerning.

An FMD outbreak in the United States would be nothing short of catastrophic for its livestock industries. FMD is a disease caused by a highly contagious virus that infects cattle, pigs, sheep, goats, deer, and other cloven hooved animals (2). The United States eradicated FMD within its borders in 1929; however, the virus is still present in many other countries. While not typically deadly for adult livestock, animals infected with FMD will experience diminished meat and milk production, thereby decreasing overall farm productivity and reducing revenues (2). Furthermore, an FMD outbreak would likely shut down exports of products from the livestock industry for an indefinite period of time, as U.S. access to foreign livestock and meat markets depends crucially on the disease status of domestic livestock populations (3). Taking the suspension of international trade due to an FMD outbreak into consideration, estimated cumulative losses over 10 years exceed $128 billion total for the U.S. pork and beef industries (4). An FMD outbreak would also harm other U.S. agriculture industries, with estimated cumulative 10-year losses of $1 billion for poultry producers, $44 billion for corn producers, $25 billion for soybean producers, and $2 billion for wheat producers. Critically, researchers predict significant losses, which include allied industries, irrespective of which species is initially found to have FMD, as FMD spreads among and between cattle, swine, and other cloven-hooved animals.

Upon diagnosis of FMD in the United States, state and federal officials would turn to the U.S. Department of Agriculture's (USDA) Foot and Mouth Disease Response Plan, also known as "The Red Book," to provide guidance on responding to this very contagious livestock virus (2). The Red Book describes how slowing or stopping the spread of the virus through controlling livestock and livestock-industry movements is an integral part of responding to any instance of FMD in the United States. Specifically, a 24- to 72-h state, regional, or even national standstill notice would likely be put in place. State quarantines and hold orders (movement controls) would be established on infected premises (premises with a presumptive positive case or confirmed positive case of FMD). Control areas would be established with boundaries extending at least 10 km beyond the border of the infected premises, with strictly regulated movement into, within, and out of these areas. Exact authorities and processes for instituting movement controls in response to an FMD outbreak differ state-by-state, while in some instances the USDA may even impose a federal quarantine or other movement control by federal order (2).[1]

Should an FMD outbreak occur and animal movement be halted, restarting livestock transportation in order to maintain business continuity in the beef cattle industry would be critical to animal health and well-being, food security, and the agricultural economy. Control areas would exceed 300 km^2 and could potentially contain many livestock operations. During an FMD outbreak, livestock movements and other necessary movements (e.g., feed movements) for affected operations would be facilitated by permits (5). Two broad categories of permits would be made available—specific permits allow movements connected with stopping the disease outbreak, while continuity of business permits pertain to continuing operations on premises within a control area that do not have FMD. Permit criteria may vary widely, but states, USDA's Animal and Plant Health Inspective Service, industry participants, and academia have exerted considerable resources to construct Secure Food Supply (SFS) Plans, which provide guidelines that may be sufficient for obtaining permits should an outbreak occur (5, 6).

SFS Plans have proven to be effective as disease outbreak response frameworks. In 2014–2015, guidelines from early versions of SFS Plans for poultry (Secure Turkey Supply Plan and Secure Broiler Supply Plan) and poultry products (Secure Egg Supply Plan) were employed to facilitate issuance of ∼8,000 permits that allowed for more than 20,000 movements for premises located in control areas during the highly pathogenic avian influenza outbreak (7). The Secure Beef Supply (SBS) Plan, which is an SFS Plan specific to the beef cattle industry, helps individual cattle producers prepare to obtain permits to preserve continuity of business on their own operations should an FMD outbreak occur nearby. The SBS Plan was funded by USDA and developed by the Center for Food Security and Public Health at Iowa State University in collaboration with industry, state and federal officials, and other academic institutions with the stated goals of providing "guidance for operations with cattle that have no evidence of FMD infection" and helping those farms "prepare to meet movement permit requirements" (8).[2]

Compliance with the SBS Plan requires producers to adopt enumerated components, among which are obtaining a national premises identification number from the relevant state animal health official, preparing to monitor for FMD, and implementing (or making preparations to implement) enhanced biosecurity practices (8). A working definition of biosecurity is procedures that livestock producers can implement to prevent disease transmission across and within operations, with so-called enhanced biosecurity practices in the SBS Plan selected given known FMD exposure routes. The SBS Plan self-assessment checklist describes many enhanced biosecurity procedures, but the "Guide to the Secure Beef Supply Plan" (Guide) strongly recommends pre-outbreak implementation of having a biosecurity manager, having a written operation-specific enhanced biosecurity plan, and having a line of separation (LOS) around each operation (8). A biosecurity manager is the individual tasked with developing the operation-specific enhanced biosecurity plan. The biosecurity manager may work with a veterinarian to develop the plan, and plan templates are

[1] An example of a federal order instituting movement controls in several counties in Texas and New Mexico following the 2002–2003 Newcastle disease outbreaks can be found at https://www.govinfo.gov/content/pkg/FR-2003-04-16/pdf/FR-2003-04-16.pdf.

[2] More information regarding the SBS Plan is available online at: https://securebeef.org/.

available online at the SBS Plan website. Finally, an LOS is a clear boundary that distinguishes off-operation movements from on-operation movements (8).

If a producer identifies a presumptive case of FMD, the Red Book specifies that enhanced biosecurity practices be employed before the positive case is even confirmed (2). The Red Book suggests that implementation of enhanced biosecurity should happen in the first 24 h after initial FMD case identification regardless of the specific details. While such a quick response would be absolutely necessary to curtail the outbreak, farmers in a control area would not have much time to react to what would certainly be a chaotic situation. However, adoption of the SBS Plan before an outbreak occurs helps farmers prepare to respond quickly (8). Notably, the three pre-outbreak practices strongly recommended by the Guide are largely preparatory. Other related, and sometimes overlapping, enhanced biosecurity practices are listed in the Guide and other operation-type specific checklists (9, 10). Adoption of these additional practices is encouraged since heightened biosecurity offers protection against endemic diseases. Additionally, preparations made before an outbreak could facilitate adoption of this enhanced biosecurity during an FMD outbreak. The SBS Plan, however, does not strictly recommend implementation of these extra practices until an outbreak occurs. For instance, in reference to cleaning and disinfection (C&D) stations, the checklist for pasture cattle suggests having "an operational, clearly marked, and equipped C&D station ready to be used in the event of an FMD outbreak" (10). The distinction is made because, depending on the practice, implementing enhanced biosecurity can be both inconvenient and expensive, and the full benefits may not be realized unless an outbreak occurs. By comparison, adoption of the three pre-outbreak practices requires relatively minimal monetary investment.

Benchmarking producer adoption of enhanced biosecurity outlined by the SBS Plan is of utmost importance to the U.S. cattle industry for many reasons, including reducing uncertainty regarding industry-wide preparedness. Identifying how many, whom, where, and why cattle producers implement biosecurity practices has value to many segments of the beef production system (and other species given the nature of FMD). Insights regarding the adoption of the three pre-outbreak practices and the relationship that has with the perceived ability to adopt other enhanced biosecurity practices are of particular importance should an FMD outbreak occur. If adoption of these pre-outbreak practices is positively correlated with perceived feasibility of adopting the other biosecurity measures during an FMD outbreak, it would suggest that the SBS Plan's recommendation of adopting the pre-outbreak practices may be effective in facilitating an FMD response that better maintains continuity of business.

MATERIALS AND METHODS

Data

This research uses data from a 2018 survey of U.S. cattle producers. Sampling, survey administration, and data collection were done in collaboration with BEEF Magazine, a leading national publication for cow-calf operators, stocker-growers, cattle feeders, veterinarians, nutritionists and allied industries.[3] Different survey versions were employed, with cattle operation characteristics determining which version a producer received. The three versions included surveys for a cow-calf operation, a feedlot operation, and a cattle operation. A producer qualified for the cow-calf operation survey if the operation had at least 20 beef cows in inventory, qualified for the feedlot operation survey if the operation had sold at least 50 head of fed cattle in the last 12 months, and qualified for the cattle operation survey if the operation had at least 20 head of any cattle in inventory. Cattle inventory thresholds used to determine survey eligibility were based on internal data BEEF Magazine uses for their membership subscriptions. The cow-calf operation and cattle operation versions of the survey targeted seedstock and cow-calf operations, and the feedlot operation version targeted stocker/backgrounder and feedlot operations.[4]

Printed survey invitation packets were mailed to a random sample of 1,500 producers eligible for the cow-calf survey, 1,500 producers eligible for the feedlot survey, and 2,000 producers eligible for the cattle survey. Survey invitation packets were mailed on October 22, 2018. A $1 bill, cover letter, and postage-paid return envelope were included in each invitation packet (11). Oerly, Tonsor, and Mitchell (12–14) provide additional details on survey data collection and response. Response rates were 22% for the cow-calf survey, 22% for the cattle survey, and 13% for the feedlot survey. The useable sample was reduced further, in some instances, due to limited non-response for specific survey questions. Survey questions regarding SBS Plan biosecurity adoption and operation characteristics were consistent across survey versions, enabling pooling of cow-calf and cattle operation survey respondents. We refer to them as cow-calf producers for the purposes of this analysis. The two broad categories surveyed, cow-calf producers and feedlot producers, capture most of the U.S. cattle supply chain, which is important as it allows for more complete benchmarking.

In addition to being asked questions regarding producer and operation characteristics, survey participants were presented with two lists of enhanced biosecurity practices. The first list included the SBS plan pre-outbreak practices of having a biosecurity manager (*Biosecurity Manager*) and having a written operation-specific biosecurity plan (*Biosecurity Plan*) as well as other enhanced biosecurity practices. The second list included the pre-outbreak practice of having a defined LOS (*LOS Defined*) as well as the components of an effective LOS. See **Table 1** for a list of the enhanced biosecurity practices for which responses were elicited in the survey. In the survey, participants were asked to indicate whether or not they used a particular practice. Producers were also asked to provide a feasibility rating for implementation of the biosecurity practice in the event of an

[3]Beef Magazine is part of the Informa Markets Division of Informa PLC. More information about BEEF Magazine is available online at: https://www.beefmagazine.com.

[4]An overview of the U.S. cattle industry, including a discussion of the cow-calf and feedlot (i.e., cattle feeding) sectors, as well as other features such as live cattle international trade, is available online at: https://www.ers.usda.gov/topics/animal-products/cattle-beef/sector-at-a-glance/.

TABLE 1 | Secure Beef Supply Plan enhanced biosecurity practice definitions.

Enhanced Biosecurity Practices	
Biosecurity Manager	**There is a designated biosecurity manager for the operation**
Biosecurity Plan	**An operation-specific, written, enhanced biosecurity plan has been developed**
Animal Origin	Animals come only from sources with documented enhanced biosecurity practices
Contingency Plan	A plan exists to manage animals in a biosecure manner on-site in the event animal movement is stopped for several weeks
Feed Storage	Feedstuffs are delivered, stored, mixed, and fed in a manner that minimizes contamination, and feed spills are cleaned up promptly
LOS Defined	**A line of separation is clearly defined and marked on the operation**
Access Points	Entry to the operation is restricted to a limited number of access points
Nose-to-Nose	Nose-to-nose contact with livestock on adjacent premises is prevented
Essential Individuals	Access is limited to individuals who are essential to the operation
Vehicles Clean	Vehicles, trailers, and equipment that cross the LOS are properly cleaned and disinfected
One-Way Exit	Animals leaving the operation only move in one direction across the LOS at an Access Point
Loading Area	The area designated for loading/unloading animals is not a people entry point
Areas Clean	Areas contaminated by personnel or animals after loading/unloading are properly cleaned and disinfected

Pre-outbreak practices are in bold. Indented practices are specific components of an LOS.

FMD outbreak. Feasibility ratings were presented as a Likert scale (1 = highly infeasible, 2 = infeasible, 3 = neutral, 4 = feasible, and 5 = highly feasible). The feasibility-of-adoption responses provide novel data regarding producer attitudes about adopting biosecurity measures during an FMD outbreak.

Analysis

Mean adoption rates and mean feasibility ratings for the SBS Plan enhanced biosecurity practices are summarized and compared for both cow-calf and feedlot producers. The mean adoption rates provide a much-needed benchmark for where the industry is at in regard to biosecurity adoption aimed at known FMD exposure routes. Maintaining continuity of business during an FMD outbreak will require participation from all segments of the supply chain, thus we make comparisons across operation type for specific practices. We conduct both the benchmarking and the industry segment comparisons using cross tabulations, with results presented in **Table 2**.

In **Table 2**, we also evaluate how operation size is correlated with enhanced biosecurity practice adoption for both cow-calf and feedlot producers. Benchmarking biosecurity adoption conditional on operation size is important because, in the United States, relatively few cow-calf and feedlot operations control most of the cattle inventory

TABLE 2 | Enhanced biosecurity practice adoption proportions and mean feasibility ratings.

	Biosecurity Manager (Pre-Outbreak Practice)	Biosecurity Plan (Pre-Outbreak Practice)	Animal Origin	Contingency Plan	Feed Storage	LOS Defined (Pre-Outbreak Practice)	Access Points	Nose-to-Nose	Essential Individuals	Vehicles Clean	One-Way Exit	Loading Area	Areas Clean
Cow-Calf													
Adoption rate Overall (N = 303)	0.09	0.04	0.13	0.16	0.39	0.12	0.23*	0.20	0.21	0.09	0.17	0.17	0.06
1–49 cows (N = 36)	0.11	0.00	0.14	0.22	0.44	0.14	0.31	0.33	0.25	0.06	0.25	0.22	0.11
50–199 cows (N = 152)	0.06	0.04	0.11	0.13	0.36	0.12	0.22	0.22	0.21	0.08	0.16	0.16	0.07
200+ cows (N = 104)	0.13	0.06	0.14	0.18	0.42	0.12	0.21	0.13	0.21	0.10	0.14	0.13	0.04
Feasibility (N = 303)	2.69 (1.38)	2.84 (1.21)	3.29 (1.25)	3.30 (1.20)	3.84 (1.13)	2.90 (1.24)	3.21 (1.31)	2.85 (1.36)	3.33 (1.30)	2.98 (1.25)	3.17 (1.25)	3.07 (1.25)	2.85 (1.21)
Feedlot													
Adoption rate Overall (N = 58)	0.14	0.07	0.17	0.24	0.47	0.12	0.34*		0.26	0.14	0.21	0.16	0.10
1–999 head capacity (N = 47)	0.13	0.02	0.15	0.19	0.45	0.06	0.30		0.21	0.11	0.19	0.09	0.09
1,000+ head capacity (N = 10)	0.20	0.30	0.30	0.40	0.50	0.30	0.50		0.50	0.30	0.30	0.40	0.20
Feasibility (N = 58)	2.93 (1.41)	2.88 (1.31)	3.14 (1.25)	3.31 (1.25)	3.79 (1.10)	3.07 (1.36)	3.43 (1.38)		3.34 (1.28)	3.02 (1.32)	3.16 (1.23)	2.97 (1.23)	2.88 (1.19)

*Mean feasibility ratings are in terms of a Likert scale (1 = highly infeasible, 2 = infeasible, 3 = neutral, 4 = feasible, and 5 = highly feasible), with standard deviations in parentheses. Cow-calf and feedlot operation size categories are derived from USDA's National Animal Health Monitoring System studies (15, 16). For both cow-calf and feedlot producers, producers who did not answer the operation size question were included in the calculation of overall adoption rates and mean feasibility ratings to maintain consistency with **Table 4** and **Figure 1**, but could not be included in the calculation of the operation-size-specific adoption rates.*

**Represent (according to Fisher's exact-tests) statistically significant differences in overall adoption rates for cow-calf and feedlot producers at $P < 0.10$. No statistically significant differences in mean feasibility ratings for cow-calf and feedlot producers were demonstrated (according to Wilcoxon rank-sum tests) at $P < 0.10$.*

(17). This means that overall adoption may not provide a true understanding of industry preparedness for an FMD outbreak if, for instance, overall rates are low, but most of the largest operations have adopted the enhanced biosecurity practices. Previous literature provides some suggestive evidence as there appears to be economies of size in biosecurity adoption (18, 19).

The literature also shows correlations between geographic location and cattle producer adoption behavior and perceptions (20–22). Beef cow inventory and operations, in particular, are widely dispersed throughout the United States. These operations interact with widely diverse human, ecological, and climatic environments in their respective regions that could impact production practice choices (23). For example, SBS Plan biosecurity materials highlight that cleaning and disinfecting "can be difficult in the winter in northern climates" (24). Potential solutions such as building a sheltered cleaning and disinfecting station could be prohibitively expensive, especially if it is only employed in the event of an FMD outbreak (24). Less obvious, but equally important for preserving continuity of business during an FMD outbreak are legal environments that vary according to jurisdiction (6). For instance, according to currently published state guidance, Kansas intends to require permits for all movements state-wide following any instance of FMD in North America, which is a much more stringent permitting policy than other states (6, 25). To benchmark possible regional differences for enhanced biosecurity adoption, **Table 3** presents, by region, adoption rates for the three pre-outbreak practices.

In addition to the primary objective of benchmarking SBS Plan biosecurity adoption, the SBS Plan strongly recommending pre-outbreak adoption of certain practices suggests another specific objective for this study. Namely of interest is how adoption of the three pre-outbreak practices correlates with producers' perceived feasibility of adopting additional biosecurity practices should an FMD outbreak occur. The survey data allows for this unique analysis, which we perform using cross tabulations. Specifically, **Table 4** presents mean feasibility ratings of all biosecurity practices for both adopters and non-adopters of each of the pre-outbreak practices.

The analysis in **Table 4** is closely related to complementarity. Simply put, complementarity with respect to biosecurity suggests that adoption of a particular practice might be made more cost effective by earlier or concurrent implementation of other biosecurity practices, or that the marginal efficacy of implementing an additional biosecurity practice may be increased by the implementation of others (18, 20, 26). To more directly examine whether or not complementarity might be a driver of increased adoption of all biosecurity, we use stacked bar charts in **Figure 1** that depict the number of additional practices adopted conditional on the adoption of a given biosecurity practice. If a large number of the producers who have adopted *Biosecurity Manager*, for example, have also adopted most of the other practices, this is suggestive evidence that having a biosecurity manager is complementary with the other practices.

RESULTS AND DISCUSSION

Mean Adoption Rates and Feasibility Ratings

Table 2 shows mean adoption rates and mean feasibility ratings for all SBS Plan enhanced biosecurity practices for both cow-calf and feedlot producers. For instance, 9% of cow-calf producers have adopted *Biosecurity Manager*, and the mean feasibility rating for adoption of this during an FMD outbreak is 2.69, which is somewhat infeasible if 3.0 is considered neutral. At the same time, 14% of feedlots have a biosecurity manager, and the mean feasibility rating from feedlots is closer to neither infeasible nor feasible at 2.93. Especially concerning is that so few respondents have adopted *Biosecurity Plan*, with only 4% of cow-calf producers and 7% of feedlot operators adopting this practice.

Not all adoption rates are as low as having a biosecurity plan; however, **Table 2** shows that current adoption of the enhanced biosecurity practices is generally low for both cow-calf and feedlot operations—25% or lower for most of the practices. The exceptions are ensuring feedstuffs are handled properly and feed spills are cleaned up (*Feed Storage*) for both cow-calf and feedlot producers, restricting operation entry to a limited number of access points (*Access Points*) for feedlot producers, and limiting access to the operation to essential individuals (*Essential Individuals*) for feedlots. For both cow-calf and feedlot producers, *Feed Storage* has the highest adoption, which is a practice that might have higher adoption rates before an FMD outbreak for reasons other than biosecurity.

Broadly speaking, adoption rates for all biosecurity practices are similar for both cow-calf and feedlot producers, with Fisher's exact-tests showing that only *Access Points* has statistically different adoption for cow-calf and feedlot producers. Specifically, the adoption rate for *Access Points* is 23% for cow-calf producers and 34% for feedlots. Practically speaking, limiting access points is easier and less costly for feedlots given typical feedlot layouts and the smaller land area required for confined feedyards on most feedlot operations in comparison to range land or pastures for cow-calf operations (17). The lack of statistical differences in adoption could follow, at least in part, from the small sample size for feedlots as well as low adoption rates by both producer types. With this being the case, other adoption rate differences, while not statistically significant, could similarly reflect differences in day-to-day operation requirements for cow-calf and feedlot producers.

Only cow-calf operations were asked about preventing nose-to-nose contact with livestock on adjacent premises (*Nose-to-Nose*) since feedlot operations are not usually located as close to each other as cow-calf operations. The mean feasibility rating for adopting *Nose-to-Nose* during an FMD outbreak is 2.85, which is slightly infeasible and tied for third-lowest among all practices for cow-calf producers. Though implementation of this practice would be of utmost importance for a cow-calf producer in a control area should an outbreak occur on a nearby operation, the low mean feasibility rating likely reflects the difficulties of moving cattle from one pasture to another or adjusting pasture boundaries within 24 h. Implementing this practice before an outbreak could seriously impact pasture use, with low current

TABLE 3 | U.S. beef cow inventory, operations with beef cows, and pre-outbreak biosecurity practice adoption for cow-calf producers by region.

	Regional Totals		Cow-Calf Adoption (N = 302)		
Region	Head (1,000 s)	Operations (number)	Biosecurity Manager	Biosecurity Plan	LOS Defined
Cornbelt (IA, IL, IN, MO, OH)	3,858	109,918	0.16	0.05	0.11
Northern Crescent (CT, DE, MA, MD, ME, MI, MN, NH, NJ, NY, PA, RI, VT, WI)	1,182	63,930	0.05	0.03	0.05
Northern Plains (KS, ND, NE, SD)	6,123	62,247	0.05	0.03	0.05
Northwest (AK, AZ, CA, CO, HI, ID, MT, NM, NV, OR, UT, WA, WY)	6,216	90,479	0.09	0.02	0.09
South (AL, AR, FL, GA, KY, LA, MS, NC, SC, TN, VA, WV)	7,269	222,142	0.12	0.06	0.27
Southern Plains (OK, TX)	6,669	180,330	0.08	0.06	0.14
Total	31,317	729,046	0.09	0.04	0.12

Regions used in the analysis were adapted from Schulz and Tonsor (21), who use USDA Economic Research Service (ERS) farm production regions combining the lake states and northeast regions (Northern Crescent), the mountain and Pacific regions (Northwest), and the southeast region, Appalachia region, and delta states (South). Inventory (head) numbers are January 1 estimates from the USDA-NASS Cattle report (28). Operation numbers are from the 2017 Census of Agriculture (29).

adoption (20%) reflecting that most producers either are unaware of this biosecurity practice or consider it impractical and/or too costly until an actual disease outbreak.

Finally, mean adoption rates and feasibility ratings for the three pre-outbreak practices are generally among the lowest of all the biosecurity measures considered. This reveals that, concurrently, relatively few producers have adopted these pre-outbreak practices and they think it is relatively infeasible to do so should an outbreak occur. This makes sense—finding a biosecurity manager, while it likely requires minimal monetary investment, requires time and could be a very difficult action to execute in 24 h. Furthermore, in an outbreak scenario, many of the other enhanced biosecurity practices would be more urgent and their immediate implementation could take precedence over the pre-outbreak practices. For instance, producers in a control area would likely ensure that vehicles, trailers, and other equipment crossing the LOS are clean and disinfected (*Vehicles Clean*) before stopping to construct a written biosecurity plan. That said, having a biosecurity manager and developing a biosecurity plan may increase the feasibility of adopting *Vehicles Clean* at short notice.

Adoption by Operation Size and Region

Table 2 also presents cow-calf and feedlot producer mean adoption rates for the enhanced biosecurity practices by operation size. Tests of statistical differences across operation size are not performed due to small sample sizes and low adoption rates, but some insights can still be gleaned. For cow-calf operations, operation size is correlated with adoption differently depending on which biosecurity practice is being considered. Consider adoption rates for *Biosecurity Plan* and *Vehicles Clean*, which are positively correlated with operation size. In comparison, adoption appears to decrease with size for *Nose-to-Nose*.

Adoption of capital intensive biosecurity practices such as *Vehicles Clean* is likely more economically viable for large commercial producers since they have more financial resources at their disposal. Furthermore, large producers could spread out the per-head costs over larger volumes of cattle (22). Adoption of managerial-intensive biosecurity practices such as *Biosecurity Plan* could also be easier for larger producers as they typically engage in less off-farm employment and work more hours on the farm (27). Conversely, practices like *Nose-to-Nose* could have lower adoption for larger producers because they could be exponentially more expensive to implement on a larger scale. It is possible that *Nose-to-Nose* could be less costly and more convenient on smaller scale cow-calf operations that require fewer and smaller pastures.

For feedlots, **Table 2** shows that operations with a capacity of 1,000 or more head have higher adoption rates for every enhanced biosecurity practice compared to operations with a capacity of <1,000 head. According to the USDA, feedlots with a capacity of 1,000 head or more market more than 80% of fed cattle in the United States (17). There are, however, many more small feedlots, with 95% of U.S. feedlots having a capacity of <1,000 head (17). This makes gauging feedlot industry preparedness more difficult. Larger feedlots, while fewer in number, may be more prepared and because of this may face lesser movement restrictions, thereby helping maintain continuity of business for a large share of the U.S. cattle on feed inventory. On the other hand, smaller feedlots represent the vast majority of operations and might not be in a position to implement enhanced biosecurity and subsequently obtain necessary permits to move cattle in a timely manner. There is no obvious answer as to which measure—cattle inventory or number of operations—is a better metric for evaluating preparedness of the cattle industry. Operations and inventory can be thought of as links in a chain; a biosecurity program is only as strong as its weakest link.

Similar challenges exist as to what metric to use when benchmarking regional preparedness. **Table 3** shows that adoption of pre-outbreak practices varies (sometimes widely) by region. For example, the highest adoption for *LOS Defined* is in the South, where 27% of surveyed cow-calf producers said they have adopted this practice. The lowest adoption rates for *LOS Defined* are in the Northern Crescent and Northern Plains, both

TABLE 4 | Enhanced biosecurity practice mean feasibility ratings conditional on adoption of pre-outbreak biosecurity practices for cow-calf and feedlot producers.

		Biosecurity Manager (Pre-Outbreak Practice)	**Biosecurity Plan (Pre-Outbreak Practice)**	**Animal Origin**	**Contingency Plan**	**Feed Storage**	**LOS Defined (Pre-Outbreak Practice)**	**Access Points**	**Nose-to-Nose**	**Essential Individuals**	**Vehicles Clean**	**One-Way Exit**	**Loading Area**	**Areas Clean**
Cow-Calf (*N* = 303)														
Biosecurity Manager	Not adopted	2.55* (1.30)	2.79* (1.20)	3.25* (1.22)	3.26* (1.18)	3.82 (1.14)	2.85* (1.22)	3.16* (1.31)	2.80* (1.35)	3.27* (1.30)	2.94* (1.26)	3.13 (1.25)	3.01* (1.24)	2.81* (1.22)
	Adopted	4.07* (1.33)	3.41* (1.25)	3.74* (1.40)	3.70* (1.27)	4.07 (1.07)	3.44* (1.34)	3.78* (1.19)	3.33* (1.39)	3.96* (1.19)	3.41* (1.12)	3.52 (1.19)	3.67* (1.24)	3.26* (1.10)
Biosecurity Plan	Not adopted	2.67 (1.35)	2.81* (1.18)	3.28 (1.23)	3.29 (1.19)	3.83 (1.12)	2.88 (1.23)	3.18* (1.31)	2.83 (1.35)	3.29* (1.29)	2.96 (1.25)	3.14* (1.24)	3.04* (1.25)	2.82* (1.21)
	Adopted	3.08 (1.89)	3.54* (1.71)	3.62 (1.50)	3.62 (1.39)	3.92 (1.38)	3.38 (1.56)	3.85* (1.14)	3.15 (1.46)	4.31* (1.11)	3.38 (1.33)	3.77* (1.17)	3.69* (1.18)	3.54* (1.05)
LOS Defined	Not adopted	2.65 (1.35)	2.79* (1.20)	3.28 (1.24)	3.25* (1.18)	3.79* (1.14)	2.78* (1.19)	3.08* (1.30)	2.78* (1.34)	3.24* (1.31)	2.94 (1.27)	3.09* (1.24)	2.99* (1.24)	2.80* (1.22)
	Adopted	2.94 (1.57)	3.25* (1.27)	3.42 (1.27)	3.69* (1.26)	4.17* (1.00)	3.83* (1.23)	4.17* (0.94)	3.39* (1.34)	4.03* (1.00)	3.25 (1.11)	3.72* (1.14)	3.72* (1.19)	3.22* (1.10)
Feedlot (*N* = 58)														
Biosecurity Manager	Not adopted	2.66* (1.32)	2.74* (1.29)	3.04 (1.26)	3.18* (1.27)	3.68* (1.11)	2.90* (1.33)	3.36 (1.38)		3.24 (1.29)	2.88* (1.27)	3.00* (1.23)	2.82* (1.21)	2.86 (1.16)
	Adopted	4.63* (0.52)	3.75* (1.16)	3.75 (1.04)	4.13* (0.64)	4.50* (0.76)	4.13* (1.13)	3.88 (1.36)		4.00 (1.07)	3.88* (1.36)	4.13* (0.64)	3.88* (0.99)	3.00 (1.41)
Biosecurity Plan	Not adopted	2.85* (1.35)	2.78* (1.28)	3.09 (1.25)	3.22* (1.24)	3.72* (1.11)	3.00 (1.36)	3.39 (1.34)		3.30 (1.27)	3.00 (1.27)	3.09 (1.23)	2.91 (1.23)	2.91 (1.15)
	Adopted	4.00* (2.00)	4.25* (0.96)	3.75 (1.26)	4.50* (0.58)	4.75* (0.50)	4.00 (1.15)	4.00 (2.00)		4.00 (1.41)	3.25 (2.06)	4.00 (0.82)	3.75 (0.96)	2.50 (1.73)
LOS Defined	Not adopted	2.75* (1.37)	2.76* (1.32)	3.00* (1.26)	3.20* (1.28)	3.71 (1.14)	2.92* (1.35)	3.37 (1.37)		3.29 (1.29)	2.90* (1.27)	3.06 (1.24)	2.82* (1.21)	2.78* (1.15)
	Adopted	4.29* (0.95)	3.71* (0.95)	4.14* (0.38)	4.14* (0.38)	4.43 (0.53)	4.14* (0.90)	3.86 (1.46)		3.71 (1.25)	3.86* (1.46)	3.86 (0.90)	4.00* (0.82)	3.57* (1.27)

Mean feasibility ratings are in terms of a Likert scale (1 = highly infeasible, 2 = infeasible, 3 = neutral, 4 = feasible, and 5 = highly feasible), with standard deviations in parentheses.
**Represent (according to Wilcoxon rank-sum tests) statistically significant differences in mean feasibility ratings conditional on the adoption of the pre-outbreak practice on the vertical axis at $P < 0.10$.*

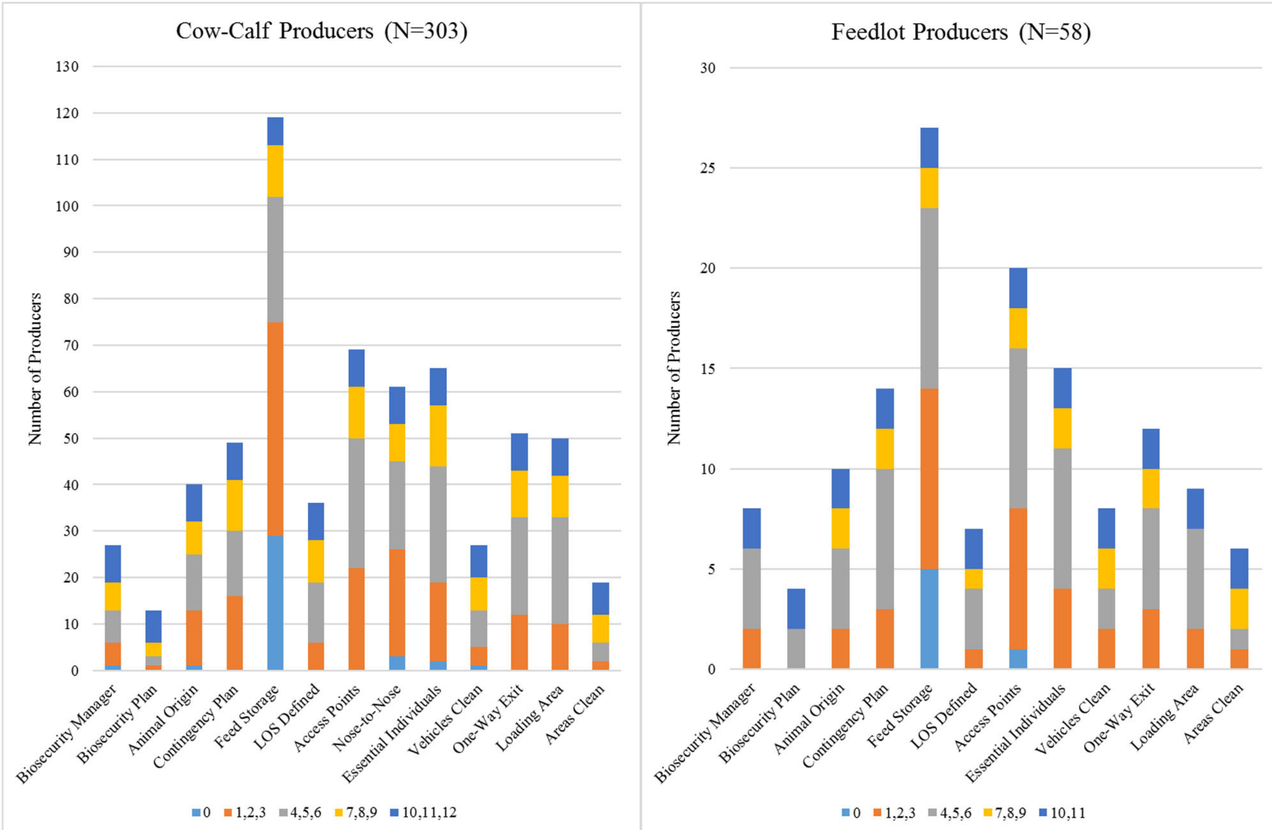


FIGURE 1 | Complementarity of enhanced biosecurity practices as shown by number of other practices adopted by adoptees of a given practice. The vertical axis shows how many producers in *N* have adopted the practice named on the horizontal axis. Categories are combined for the sake of readability.

at 5%. High adoption in the South is encouraging since it is the largest of the production regions in terms of cattle inventory and operations, accounting for 23% of U.S. beef cow inventory and 30% of U.S. farms with beef cows. Nearly 20% of the U.S. beef cow inventory is in the Northern Plains, compared to <4% in the Northern Crescent; however, the number of operations with beef cows in both regions is nearly equal (about 9%). If having high adoption rates in regions with more inventory is the goal, more resources should be dedicated to the Northern Plains region to help increase overall SBS Plan uptake. Alternatively, it may be desirable to dedicate more time and resources to reaching smaller producers in the Northern Crescent.

Conditional Feasibility Ratings

Table 4 shows the relationship between current adoption of the pre-outbreak practices and perceived feasibility of adoption during an FMD outbreak. Specifically, we measure mean feasibility for all of the enhanced biosecurity practices conditional on the adoption of each of the three pre-outbreak practices. For example, cow-calf producers who have a biosecurity manager have a mean feasibility rating of 3.74 for ensuring that animals come only from sources that document enhanced biosecurity practices (*Animal Origin*). This is statistically higher than the corresponding feasibility rating of 3.25 for those cow-calf producers who do not have a biosecurity manager. This demonstrates that, in this case, having a biosecurity manager correlates with higher perceived feasibility of implementing enhanced biosecurity during an FMD outbreak.

Overall, several patterns emerge in **Table 4**. For nearly every practice, for both cow-calf and feedlot producers, mean feasibility ratings conditional on adoption of any of the three pre-outbreak practices are higher than the comparable mean feasibility ratings conditional on non-adoption of any of the three pre-outbreak practices. In many cases, mean feasibility ratings are statistically different. While correlation is not causation, the results suggest that adopting the three pre-outbreak practices would encourage adoption in the event of an FMD outbreak. Thus, the main result from **Table 4** is that the SBS Plan strongly recommending, or even going further and incentivizing in some manner, adoption of the three pre-outbreak practices may succeed in helping producers prepare to adopt the enhanced biosecurity practices during an outbreak, as evidenced by higher perceived feasibility ratings regarding later adoption of those practices.

Some practices have feasibility ratings that are not significantly correlated with current adoption of the pre-outbreak practices. For cow-calf operations, mean feasibility ratings for *Feed Storage* are not correlated with having a biosecurity manager or biosecurity plan. Producers obtain benefits from careful feedstuff storage (e.g., reduced feed loss and spoilage) regardless of whether or not an FMD outbreak occurs (30). Storing feed properly has a cost, however. The lack of correlation between *Feed Storage* feasibility ratings and adoption of the pre-outbreak practices, in conjunction with relatively high current adoption of *Feed Storage*, suggests that for many producers the benefits must outweigh the increased storage costs irrespective of FMD considerations. Feedlot producers, who had a relatively high adoption rate for *Access Points*, demonstrate no significant correlation between feasibility ratings for that practice and adoption of any of the three pre-outbreak practices. In fact, this is the only practice for which mean feasibility is not statistically correlated with even one of the pre-outbreak practices. This result could, again, reflect the ability for feedlots to more readily limit the number of access points.

Several other findings further point to the internal consistency of the results in **Table 4**. First, intuitively, mean feasibility ratings for implementing a pre-outbreak practice during an outbreak are always higher among adopters of that same practice compared to non-adopters of that practice. For instance, feedlot producers who do not have a biosecurity manager have a mean feasibility rating for having a biosecurity manager during an outbreak of 2.66, which is lower than the rating of 4.63 for producers who already have a biosecurity manager. Furthermore, in both segments, producers who have a biosecurity manager think having an operation-specific biosecurity plan in an outbreak is more feasible than producers who do not have a biosecurity manager. This is important because, as discussed in SBS Plan documentation, it is the biosecurity manager who helps develop the operation-specific biosecurity plan, suggesting there is complementarity in adoption of those practices (9, 10).

Complementarity Analysis

Results for the complementarity analysis, presented in **Figure 1**, extend the results from **Table 4**. Consider the first bar (*Biosecurity Manager*) in the cow-calf producer panel. The vertical axis shows that only 27 of the $N = 303$ cow-calf producers currently have a biosecurity manager. While those 27 producers comprise a small proportion of the sample of 303 producers, the dark blue portion of the bar shows that 8 of these 27 producers have adopted 10 or more of the other enhanced biosecurity practices. Similarly, the second bar in the cow-calf producer panel shows only 13 producers have adopted *Biosecurity Plan*, but the dark blue portion of the bar shows that 7 of these 13 producers have adopted 10 or more of the other practices. Conversely, very few cow-calf or feedlot producers have adopted the three pre-outbreak practices without adopting any other practices. Admittedly, these results are not exclusive to the pre-outbreak practices. For example, ensuring that loading areas are clean (*Areas Clean*) presents similar results. That said, there are certain practices for which complementarity does not hold. For example, 29 out of 303 total cow-calf producers and 5 out of 58 total feedlot producers adopted *Feed Storage* without adopting a single other enhanced biosecurity practice.

The results of the complementarity analysis have several potential explanations. The high rates of co-adoption among adoptees of certain practices indicates that there could be cost and/or efficiency benefits that drive adopters of the pre-outbreak practices to adopt the majority of the other practices. This explanation is not all-encompassing as fewer than 2% of cow-calf producers have adopted every enhanced biosecurity practice compared to 49% of cow-calf producers who have not adopted even a single practice (results not shown). Alternatively, it could be that many producers who adopt the pre-outbreak practices do so because it is relatively costless compared to the other 10 or more procedures they have already adopted. Either way, convincing producers to adopt the three pre-outbreak practices does not seem to reduce current adoption of other enhanced biosecurity and likely increases adoption.

Future Outreach Efforts

Much of the outreach effort to increase SBS Plan enhanced biosecurity adoption, to-date, has been on a case-by-case, state-by-state, or regional basis. For example, in March 2020, a group of state animal health officials, beef industry representatives, and trade organizations from Colorado, Kansas, Missouri, Nebraska, Oklahoma, and Texas had a regional meeting to discuss how to best implement the SBS Plan. The first of five action items the group agreed upon was, "State-based cattle associations should become more engaged in sharing information about SBS and emergency movement permitting with producers" (6). Such emphasis on state-level outreach allows industry representatives, university extension staff, and others to leverage local information and relationships. Furthermore, focused outreach efforts could support a more effective FMD response should an outbreak occur since, as Colorado's SBS Plan highlights, "Response to an animal disease outbreak will begin at the local level" (31). That said, for all the merits of localized efforts, the benchmarking in this study shows that—at least as of 2018—SBS Plan biosecurity implementation is generally very low.

It could be the case that SBS Plan biosecurity adoption is even lower than demonstrated by this study. A limitation of survey data is the potential for selection bias. In the present study, producers who are more confident in their biosecurity practices might have been more willing to respond to surveys regarding biosecurity practices (19). This could result in higher mean SBS Plan biosecurity adoption rates and feasibility ratings in the survey samples than in producer populations. Hence, this most intuitive form of potential selection bias would augment this study's primary takeaway of low adoption of SBS Plan biosecurity. This has implications for disease control and continuity of business and suggests an even greater need to increase preparedness for FMD.

A specific result from our study that SBS Plan administrators and other proponents should consider carefully is that producers in both the cow-calf and feedlot segments of the industry are somewhat more likely to have adopted enhanced biosecurity practices that are not the three pre-outbreak practices. This could be simple economics at work. Adoption of enhanced biosecurity practices could reduce costs and/or increase revenues at all times, while producers discount the potential benefits of adopting the pre-outbreak practices because they depend on an event, i.e., an FMD outbreak occurring. The chances of an FMD outbreak occurring are small and not known with certainty, making the potential benefits of adopting the pre-outbreak biosecurity difficult to enumerate.

Further research is needed to identify the exact causal mechanisms behind producers' biosecurity adoption decisions. Detailed, farm-level data for practice-specific costs could be valuable for identifying causal economic relationships. For example, the interplay between pre-outbreak and outbreak-specific costs and benefits of making sure vehicles, trailers, and equipment that cross the LOS are properly cleaned and disinfected—and the impact this has on adoption of that practice—could be more rigorously explored given farm-level fixed and variable cost data for that practice. The authors know of no such data for the U.S. beef cattle industry, so this information would need to be collected, likely through careful producer surveys and interviews. This data collection process would also present the opportunity to illicit responses that could be leveraged in sociological and/or psychological analyses. For example, both Ellis-Iversen et al. (32) and Alarcon et al. (33) utilize interview data and socio-psychological models to identify factors driving disease control practices by livestock farmers in the United Kingdom. Studies of this kind would add to existing research and could be very important for increasing FMD preparedness, since as noted in a recent review, "human adoption and adherence to biosecurity practices is influenced by psychosocial factors and is an area of urgent research and policy consideration" (34).

Each farmer's biosecurity decisions are influenced by unique factors, economic and otherwise, including social, psychological, and contextual considerations (34). This means there is no one-size-fits-all approach to increase participation in SBS Plan biosecurity. Moving forward, however, perhaps a targeted national "train the trainer" program would be beneficial. Such a program could be used to equip regional, state, and local entities with materials that highlight the potential benefits and relatively low costs of adopting the SBS Plan's recommended pre-outbreak practices, especially in comparison to the enhanced biosecurity practices that have already been adopted. Adoption of these pre-outbreak practices could, in turn, foster producer understanding of the potential losses associated with an FMD outbreak and subsequent movement controls. The internalization of these potential costs could impact cow-calf and feedlot producers' cost-benefit calculation, thereby inducing wider adoption of all SBS Plan enhanced biosecurity practices. Such efforts, if successful in increasing SBS Plan enrollment, will not guarantee a perfect response to an FMD outbreak should one occur. However, increasing SBS Plan enhanced biosecurity is a step in the right direction for preserving continuity of business in the worst-case scenario of an FMD outbreak.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: The datasets analyzed for this study are not publicly available because they are proprietary. Request to access these datasets should be directed to Glynn T. Tonsor, gtonsor@ksu.edu.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Committee on Research Involving Human Subjects/Institutional Review Board, Kansas State University. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

CP, JM, LS, and GT made direct, substantial intellectual contribution to the work, and have given approval for its publication. All authors contributed to the article and approved the submitted version.

FUNDING

This work was supported by the USDA National Institute of Food and Agriculture, under award number 2015-69004-23273.

ACKNOWLEDGMENTS

This work benefited from discussions at the International Society for Economics and Social Sciences of Animal Health (ISESSAH) International Scientific Conference held virtually on November 11–13, 2020. The authors gratefully acknowledge Dr. James Roth for helpful comments he provided.

REFERENCES

1. U.S. Department of Agriculture: Animal and Plant Health Inspection Service, Veterinary Services. *Cow-Calf Producers' Familiarity with Cattle Diseases and Preferred Contacts and Sources of Information for Disease Outbreaks*. APHIS (2011). Available online at: https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/monitoring-and-surveillance/nahms/nahms_beef_cowcalf_studies (accessed January 25, 2021).
2. U.S. Department of Agriculture: Animal and Plant Health Inspection Service, Veterinary Services. *Foot-and-Mouth Disease Response Plan: The Red Book*. APHIS (2020). Available online at: https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/emergency-management/CT_FAD_PReP_Disease_Response_Documents (accessed January 25, 2021).
3. Pendell DL, Brester GW, Schroeder TC, Dhuyvetter KC, Tonsor GT. Animal identification and tracing in the United States. *Am J Agric Econ*. (2020) 92:927–40. doi: 10.1093/ajae/aaq037
4. Hayes DJ, Fabiosa JF, Elobeid AE, Carriquiry M. *Economy Wide Impacts of a Foreign Animal Disease in the United States*. Center for Agricultural and Rural Development. Iowa State University (2011). Working Paper 11-WP 525. Available online at: https://www.card.iastate.edu/products/publications/synopsis/?p=1283 (accessed January 25, 2021).
5. U.S. Department of Agriculture: Animal and Plant Health Inspection Service, Veterinary Services. *Permitted Movement*. APHIS (2017). Available online at: https://www.aphis.usda.gov/animal_health/emergency_management/downloads/documents_manuals/fadprep_man6-0_permit-mvmt.pdf (accessed January 25, 2021).
6. Secure Beef Supply. *SBS Secure Beef Supply Regional Planning Meeting Summary Report*. Center for Food Security and Public Health. Iowa State

University (2020). Available online at: https://securebeef.org/regulatory-officials/state-regional-projects/ (accessed April 28, 2021).

7. Roth J. *Traditional Outbreak Management Practices in the U.S.* (2017). Secure Food Supply Plans. Available online at: https://www.iowabio.org/documents/filelibrary/images/iba_events/animal_health_in_the_heartland_2016/Microsoft_PowerPoint__Traditional_O_7C0FDD057F413.pdf (accessed January 25, 2021).
8. Secure Beef Supply. *Guide to the Secure Beef Supply Plan*. Center for Food Security and Public Health. Iowa State University (2019). Available online at: http://securebeef.org/ (accessed January 25, 2021).
9. Secure Beef Supply. *Self-Assessment Checklist for Enhanced Biosecurity for FMD Prevention: Beef Feedlots*. Center for Food Security and Public Health. Iowa State University (2020). Available online at: https://securebeef.org/beef-producers/biosecurity/ (accessed January 25, 2021).
10. Secure Beef Supply. *Self-Assessment Checklist for Enhanced Biosecurity for FMD Prevention: Cattle on Pasture*. Center for Food Security and Public Health. Iowa State University (2020). Available online at: https://securebeef.org/beef-producers/biosecurity/ (accessed January 25, 2021).
11. Tonsor GT. Producer decision making under uncertainty: role of past experiences and question framing. *Am J Agric Econ*. (2018) 100:1120–35. doi: 10.1093/ajae/aay034
12. Oerly A, Tonsor GT, Mitchell J. *Biosecurity and Health Management by U.S. Cattle Producers: 2018 Survey Summary*. Kansas State University (2020). Available online at: https://www.agmanager.info/livestock-meat/cross-subject-areas/biosecurity-and-health-management-us-cattle-producers-2018-survey (accessed January 25, 2021).
13. Oerly A, Tonsor GT, Mitchell J. *Traceability, Biosecurity and Health Management by U.S. Feedlot Operations: 2018 Survey Summary*. Kansas State University (2020). Available online at: https://www.agmanager.info/livestock-meat/cross-subject-areas/traceability-biosecurity-and-health-management-us-feedlot (accessed January 25, 2021).
14. Oerly A, Tonsor GT, Mitchell J. *Traceability, Biosecurity and Health Management by U.S. Cow-Calf Operations: 2018 Survey Summary*. Kansas State University (2020). Available online at: https://www.agmanager.info/livestock-meat/cross-subject-areas/traceability-biosecurity-and-health-management-us-cow-calf (accessed January 25, 2021).
15. U.S. Department of Agriculture: Animal and Plant Health Inspection Service. *NAHMS Beef Cow-Calf Studies*. APHIS (2020). Available online at: https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/monitoring-and-surveillance/nahms/nahms_beef_cowcalf_studies/!ut/p/z1/lZLLUoMwFIafpQuWkhPaAeoOkCkoVG2LxWyYgOEyA4QhVGZ8elN146W0ZpNJ5vtOcv4EERQj0tLXqqBDxVtay_Uz0ZM1dlZgLnCwcm8wWN7Sv_MMHSA00P4DCO4XDra3IGfXBsvdGKHr-hrgOSL_8588Xfq7aLc2se0vtct8ODEsuMyfAMh0-dtzB8gEtT50wgKRjg7lVdXmHMUtLRuRpIzlScbHjNZ5IobDS8WEvBGZrPmofQGnQt-cA46v8gP4HfsFjRc1Tz__iNWmc1N22LOc9axXD73cLoehE9cKKDCOo1pwXtRMzXijwF9KycWA4u8k6pooiuK3IN_61UOzN4U1m70D7sIgsA!!/#beef2017(accessed April 17, 2021).
16. U.S. Department of Agriculture: Animal and Plant Health Inspection Service. *NAHMS Feedlot Studies*. APHIS (2021). Available online at: https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/monitoring-and-surveillance/nahms/NAHMS_Feedlot_Studies (accessed April 17, 2021).
17. U.S. Department of Agriculture: Economic Research Service. *Sector at a Glance*. ERS (2020). Available online at: https://www.ers.usda.gov/topics/animal-products/cattle-beef/sector-at-a-glance/ (accessed January 25, 2021).
18. Pudenz CC, Schulz LL, Tonsor GT. Adoption of secure pork supply plan biosecurity by U.S. swine producers. *Front Vet Sci*. (2019) 6:146. doi: 10.3389/fvets.2019.00146
19. Bottoms K, Poljak Z, Dewey C, Deardon R, Holtkamp RF. Evaluation of external biosecurity practices on southern Ontario sow farms. *Prev Vet Med*. (2013) 109:58–68. doi: 10.1016/j.prevetmed.2012.08.013
20. 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) 42:203–22. doi: 10.1017/S1074070800000274
21. Schulz LL, Tonsor GT. Cow-calf producer perceptions regarding individual animal traceability. *J Agric Appl Econ*. (2010) 42:659–77. doi: 10.1017/S1074070800003874
22. McBride WD, Mathews K. *The Diverse Structure and Organization of U.S. Beef Cow-Calf Farms*. ERS (2011). EIB-73. Available online at: https://www.ers.usda.gov/publications/pub-details/?pubid=44532 (accessed January 25, 2021).
23. U.S. Department of Agriculture: Animal and Plant Health Inspection Service, Veterinary Services. *Cow-Calf Industry Manual*. APHIS (2013). Available online at: https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/emergency-management/ct_fadprep_industry_manuals (accessed April 28, 2021).
24. Secure Beef Supply. *Information Manual for Enhanced Biosecurity for FMD Prevention: Cattle on Pasture*. Center for Food Security and Public Health. Iowa State University (2020). Available online at: https://securebeef.org/beef-producers/biosecurity/ (accessed April 28, 2021).
25. Kansas Department of Agriculture. *Secure Beef Supply (SBS Plan)*. Division of Animal Health. Available online at: https://agriculture.ks.gov/divisions-programs/division-of-animal-health/secure-food-supply/kansas-secure-beef-supply-plan (accessed April 28, 2021).
26. Khanal AR, Gillespie J, MacDonald J. Adoption of technology, management practices, and production systems in US milk production. *J Dairy Sci*. (2010) 93:6012–22. doi: 10.3168/jds.2010-3425
27. Fernandez-Cornejo J. *Off-Farm Income, Technology Adoption, and Farm Economic Performance*. ERS (2007). ERR-56. Available online at: https://www.ers.usda.gov/publications/pub-details/?pubid=45744 (accessed January 25, 2021).
28. U.S. Department of Agriculture: National Agricultural Statistics Service. *Cattle*. NASS (2020). Available online at: https://usda.library.cornell.edu/concern/publications/h702q636h (accessed January 25, 2021).
29. U.S. Department of Agriculture: National Agricultural Statistics Service. *2017 Census of Agriculture: United States, Summary and State Data*. NASS (2019). Available online at: https://www.nass.usda.gov/Publications/AgCensus/2017/index.php (accessed January 25, 2021).
30. Schwab Denise. *Controlling Feed Loss and Spoilage Important for Beef Cattle Production*. Extension and Outreach. Iowa State University (2021). Available online at: https://www.extension.iastate.edu/news/controlling-feed-loss-and-spoilage-important-beef-cattle-production (accessed April 28, 2021).
31. Colorado Department of Agriculture. *Cow-Calf Emergency Disease Response Plan* (2017). Animal Health Division. Available online at: https://ag.colorado.gov/animals/emergency-preparedness-and-response (accessed April 28, 2021).
32. Ellis-Iversen J, Cook AJC, Watson E, Nielen M, Larkin L, Wooldridge M, Hogeveen H. Perceptions, circumstances and motivators that influence implementation of zoonotic control programs on cattle farms. *Prev Vet Med*. (2010) 93:276–85. doi: 10.1016/j.prevetmed.2009.11.005
33. 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) 116:223–42. doi: 10.1016/j.prevetmed.2013.08.004
34. Mankad A. Psychological influences on biosecurity control and farmer decision-making. A review. *Agron Sus Dev*. (2016) 36:1–14. doi: 10.1007/s13593-016-0375-9

Author Disclaimer: The contents are solely the responsibility of the authors and do not necessarily represent the official views of the USDA or NIFA.

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.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 11 August 2021
doi: 10.3389/fvets.2021.648003

A Simulation Study of the Use of Vaccination to Control Foot-and-Mouth Disease Outbreaks Across Australia

Tim R. Capon[1], *Michael G. Garner*[2], *Sorada Tapsuwan*[1*], *Sharon Roche*[3], *Andrew C. Breed*[3,4], *Shuang Liu*[1], *Corissa Miller*[3], *Richard Bradhurst*[5] and *Sam Hamilton*[3]

[1] CSIRO Land & Water, Acton, ACT, Australia, [2] CSIRO Health & Biosecurity, Acton, ACT, Australia, [3] Epidemiology and One Health Section, Department of Agriculture, Water and the Environment, Canberra, ACT, Australia, [4] School of Veterinary Science, University of Queensland, Brisbane, QLD, Australia, [5] Centre of Excellence for Biosecurity Risk Analysis, The University of Melbourne, Melbourne, VIC, Australia

OPEN ACCESS

Edited by:
Salome Dürr,
University of Bern, Switzerland

Reviewed by:
Gustavo Machado,
North Carolina State University,
United States
Fernanda Dorea,
National Veterinary Institute, Sweden

***Correspondence:**
Sorada Tapsuwan
sorada.tapsuwan@csiro.au

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: 31 December 2020
Accepted: 07 July 2021
Published: 11 August 2021

Citation:
Capon TR, Garner MG, Tapsuwan S, Roche S, Breed AC, Liu S, Miller C, Bradhurst R and Hamilton S (2021) A Simulation Study of the Use of Vaccination to Control Foot-and-Mouth Disease Outbreaks Across Australia. Front. Vet. Sci. 8:648003. doi: 10.3389/fvets.2021.648003

This study examines the potential for foot-and-mouth disease (FMD) control strategies that incorporate vaccination to manage FMD spread for a range of incursion scenarios across Australia. Stakeholder consultation was used to formulate control strategies and incursion scenarios to ensure relevance to the diverse range of Australian livestock production regions and management systems. The Australian Animal Disease Spread model (AADIS) was used to compare nine control strategies for 13 incursion scenarios, including seven control strategies incorporating vaccination. The control strategies with vaccination differed in terms of their approaches for targeting areas and species. These strategies are compared with two benchmark strategies based on stamping out only. Outbreak size and duration were compared in terms of the total number of infected premises, the duration of the control stage of an FMD outbreak, and the number of vaccinated animals. The three key findings from this analysis are as follows: (1) smaller outbreaks can be effectively managed by stamping out without vaccination, (2) the size and duration of larger outbreaks can be significantly reduced when vaccination is used, and (3) different vaccination strategies produced similar reductions in the size and duration of an outbreak, but the number of animals vaccinated varied. Under current international standards for regaining FMD-free status, vaccinated animals need to be removed from the population at the end of the outbreak to minimize trade impacts. We have shown that selective, targeted vaccination strategies could achieve effective FMD control while significantly reducing the number of animals vaccinated.

Keywords: Australian animal disease spread model, AADIS, vaccination, stamping out, epidemiology, outbreak, livestock

INTRODUCTION

Foot-and-mouth disease (FMD) is recognized as the single greatest disease threat to Australia's livestock industries (1, 2). Early detection of an incursion, effective control of an outbreak, and rapid return to trade are essential to minimize the economic impact of an outbreak. Australia's policy for an FMD response is to contain, control, and eradicate the disease and re-establish the FMD-free status of Australia as quickly as possible, while minimizing social and financial disruption. The Australian Veterinary Emergency Plan (AUSVETPLAN) states that the "re-establishment of trade for affected industries would be one of the highest priorities of disease response efforts" (3).

Australia's preferred approach to control an outbreak of FMD is to use stamping out, supported by a combination of measures that include a national livestock standstill, quarantine, regional movement controls, tracing, and surveillance (3). Additional measures that may be taken if authorities consider that they would be beneficial in containing and managing the outbreak include vaccination, pre-emptive culling, zoning/compartmentalization, and risk-based movement controls. Australia invests considerable resources in preparedness and planning for emergency animal diseases, including maintaining a government- and industry-funded vaccine bank for FMD (3). Despite changes to Australian contingency plans to recognize that vaccination could be an important component of an FMD control program as soon as an outbreak is detected, it is unclear how, when, or even if vaccination should be used, and if it is used, how vaccinated animals should be managed.

Modeling studies in Australia (4–6) and overseas (7–9) have shown that vaccination is effective in reducing the duration and size of outbreak situations where disease is widespread, where there is a high rate of spread, or resources for stamping out are limited. Reports suggest that early vaccination may have allowed earlier eradication that took place in FMD outbreaks in Korea (10) and Japan (11, 12). Thus, vaccination is increasingly recognized as a useful tool in containing and eradicating FMD outbreaks. However, while vaccination can contribute to earlier eradication of disease, it will have additional costs—keeping vaccinated animals in the population will delay the period until FMD-free status is regained under the World Organization for Animal Health standards (13)—and add additional complexity to the post-outbreak surveillance for demonstrating the re-establishment of FMD-free status. These issues are of particular concern for countries with significant exports of livestock and livestock products as the use of vaccination and the presence of FMD vaccinated animals in the population could be expected to cause significant market access difficulties.

Australia has no recent experience with controlling an outbreak of FMD. Decision support tools including disease models offer valuable insights into the effectiveness of different control measures (14). In particular, the decision to vaccinate is best made early in an outbreak as vaccination is likely to perform better when implemented earlier (5). However, a decision to vaccinate early in the outbreak may result in using vaccination in situations where it may offer little to no additional benefit with implications for post-outbreak surveillance, management of vaccinated animals, and regaining FMD-free status and access to markets. Conversely, not using vaccination may lead to larger and longer outbreaks, increased control costs and greater ongoing impacts on industry and local communities.

While a number of modeling studies have already assessed FMD spread and control in Australia [e.g., (4–6)], these have tended to focus on a limited range of introduction scenarios along the eastern seaboard, representing scenarios considered to be most likely or worst-case situations for FMD introduction and spread. FMD introduction, spread, and control in other areas of Australia are poorly understood. Disease managers would benefit from a clearer understanding of how, and under what conditions, vaccination could provide benefits in terms of managing an FMD outbreak in Australia.

The objective of this study is to thoroughly investigate the possible incursion scenarios and control options available to manage an FMD outbreak, with a focus on vaccination as a disease control option. The first stage of this study elicited stakeholders' views regarding the use of vaccination as part of a control strategy, incursion scenarios, and factors affecting emergency animal disease management decisions. The second stage of the study focused on how vaccination might be applied and the effect of vaccination on the size and duration of an outbreak. Drawing on the results of the stakeholder consultations, simulations were designed to better understand the consequences of alternative approaches to incorporating vaccination into control strategies for FMD.

METHODS

Stakeholder Consultation

Inputs from Australian state and territory jurisdictional stakeholders were collected through workshops and surveys. These were conducted during April to August 2017. This research received ethics approval from the CSIRO Human Ethics research committee. Stakeholders were selected from a panel of government and industry stakeholders affiliated with Animal Health Australia (AHA). AHA is a not-for-profit public company with membership made up of Commonwealth, state and territory governments, livestock industries, service providers, and associate members. AHA manages a range of national programs on behalf of its members that improve animal and associated human health, biosecurity, market access, livestock welfare, productivity, and food safety and quality (15). Selected stakeholders were sent an email invitation by AHA to participate in the consultation process (workshops or surveys depending on their availability). Two face-to-face workshops were held, each consisting of ∼30 participants. Surveys were sent to representatives of the Australian jurisdictional governments to request information about two or three incursion scenarios of interest based on the most likely or important scenarios for FMD introduction for their jurisdiction. Details are provided in the **Supplementary Materials**.

Simulation Study Design

Simulations were conducted using the Australian Animal Disease Spread model (AADIS) (16)[1]. AADIS is a stochastic spatial simulation model that simulates livestock disease spread and control at the national scale. AADIS uses the herd as its epidemiological unit of interest. A "herd" in AADIS is defined as a group of comingling animals of the same species under the

[1]AADIS is available under license for research purposes from the Australian Government Department of Agriculture, Water and the Environment (DAWE). Please contact Andrew.Breed@awe.gov.au at the Epidemiology and One Health Section, DAWE, for more information.

same production system. There are 11 different herd types in the AADIS FMD model (**Table 1**), and this allows for common attributes such as movement patterns and biosecurity practices to be applied based on herd type.

AADIS has a hybrid architecture that combines equation- and agent-based modeling techniques. The spread of disease within a herd is represented by an SEIR compartmental equation-based model (EBM) implemented as a system of ordinary differential equations (ODEs). The parameterization of the ODE system reflects the herd's production system and the subject FMD virus strain. At the time of infection, the herd's ODE system is solved numerically to yield predictions of the proportion of the population that are infected, infectious, and have clinical signs of disease over time. The solution remains in place until an external event such as vaccination or culling acts upon the herd, triggering the resolving of the ODE system. The spread of disease between herds is modeled with a stochastic and spatially explicit agent-based approach. The model incorporates the attributes and spatial locations of individual farms, saleyards, weather stations, local government areas, and direct and indirect movement patterns. AADIS simulates disease spread in daily time steps, and FMD transmission between herds is modeled through five discrete pathways: 1—farm to farm animal movements, 2—local spread (infection of farms and herds within close geographical proximity by unspecified means), 3—indirect contact (*via* fomites or animal products), 4—animal movements *via* saleyards or markets, and 5—wind-borne spread. The proportions of infected and infectious animals in the population predicted by a herd's EBM inform the likelihood that between-herd spread will occur.

The AADIS unit of interest for the control of disease is the "farm" — defined as an establishment that has one or more herds. AADIS simulates disease control according to the availability of resources, such as personnel and vaccine, and models the suite of control measures prescribed in AUSVETPLAN (3). These control measures include movement controls of animals and fomites (national livestock standstill, regional movement restrictions, and quarantine of farms), stamping out of different farm types (culling and disposal of animals and decontamination of farms), surveillance (farmer reporting and active surveillance within declared areas), tracing (direct and indirect contacts), pre-emptive culling (dangerous contacts, ring culling, and slaughter on suspicion), and vaccination (suppressive, protective, or mass

TABLE 1 | Farm and animal populations used in the AADIS FMD model.

Farm type	Number of farms	Number of animals mean (min–max)
Extensive beef	1,331	1,909 (1,200–46,575)
Intensive beef	51,383	280 (30–7,436)
Feedlot	508	1,825 (100–39,963)
Mixed beef/sheep	21,556	242 (30–5,700)
Dairy	8,675	298 (40–2,742)
Small pigs	1,873	244 (40–4,850)
Large pigs	333	4,922 (1,000–17,896)
Sheep	22,150	1,649 (20–44,000)
Smallholder	103,641	5 (1–14)
Total	**202,775**	

This represents a synthetic farm population dataset obtained from Agricultural Census data (17) and industry data and reports. The bold values are statistically significant values.

TABLE 2 | Starting conditions for simulation study FMD incursion scenarios: seed herds and snapshots.

Incursion scenario	ID	Scenario description	Seed herd			Snapshot
			Scenario starting date	Farm type	# animals	# infected herds when FMD is first detected[a]
New South Wales	NSW1	Hobby farm in the Sydney basin	May 10	Smallholder	8	6
	NSW2	Intensive sheep in the Riverina	November 10	Sheep farm	1,210	2
	NSW3	Commercial piggery, airborne spread to dairies	July 1	Commercial piggery	4,643	9
Queensland	QLD1	Backyard pigs in South Eastern Queensland	January 10	Smallholder	9	4
	QLD2	Interstate transport of infected cattle	June 10	Intensive beef	109	13
	QLD3	Piggery in central Queensland near extensive beef region	May 1	Small pig farm	363	2
South Australia	SA1	Interstate transport of infected sheep	November 1	Mixed sheep/beef	3,271	3
Tasmania	TAS1	Sheep in southern highlands	August 10	Sheep farm	1,418	2
Victoria	VIC1	Hobby farms at Bacchus Marsh	May 1	Smallholder	12	3
	VIC2	Dairy farm in South Western Victoria	September 10	Dairy herd	516	44
	VIC3	Intensive beef in South East Victoria	October 1	Intensive beef	89	16
Western Australia	WA1	Smallholder in South West WA	May 10	Smallholder	7	10
	WA2	Commercial piggery in northern agricultural region	May 10	Commercial piggery	10,836	10

[a]*Simulated number of infected herds in the population when the first IP is confirmed at the end of the silent spread phase.*

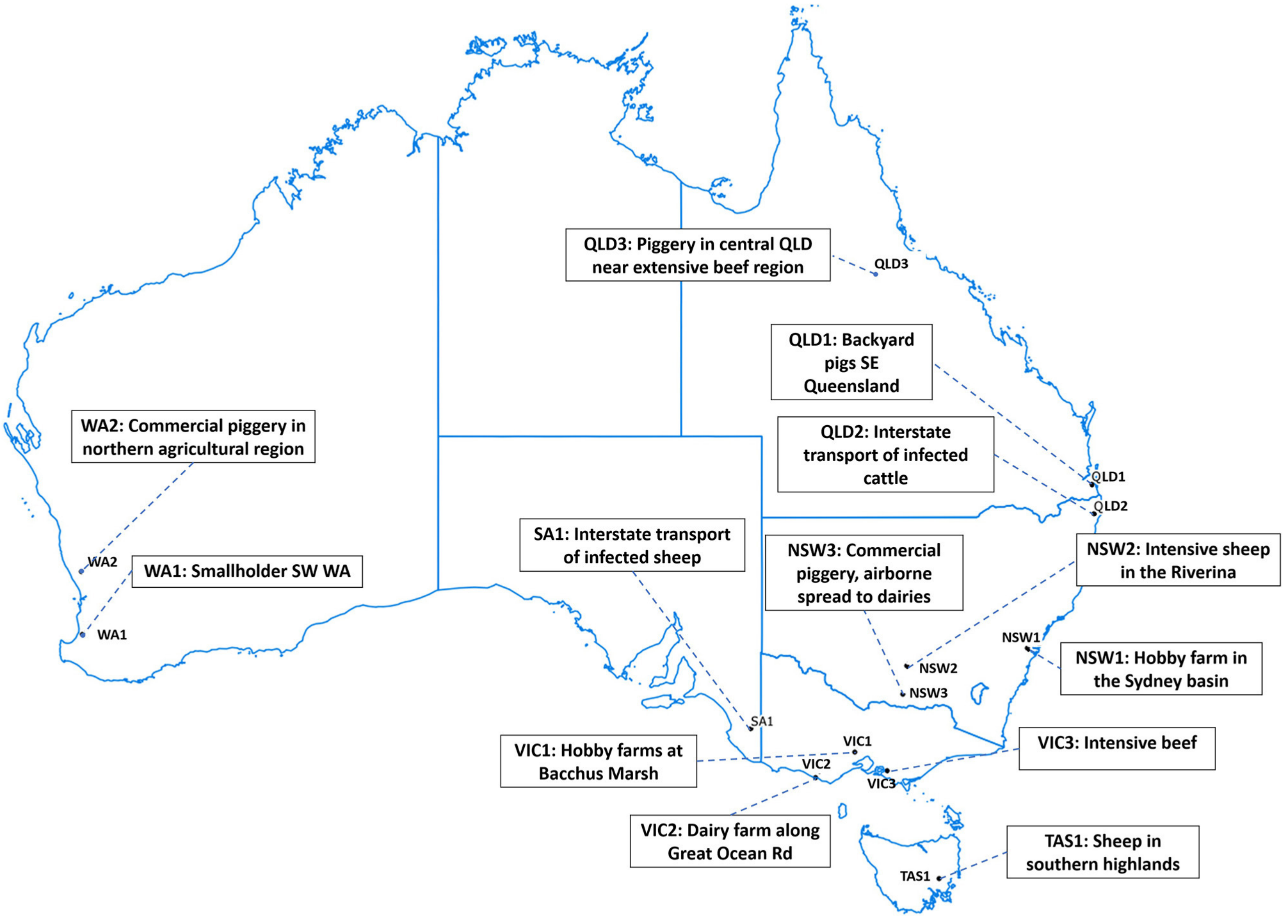


FIGURE 1 | Locations of seed herds for each incursion scenario.

vaccination). All control measures are defined and resourced per jurisdiction. Further details on AADIS can be found in Bradhurst et al. (16, 18).

To characterize the incursion scenarios and control strategies for this study, AADIS was parameterized using a combination of values estimated for previous studies (5) and values estimated through stakeholder consultation (as described in Section Stakeholder Consultation above). Details of the AADIS parameterization are provided in the **Supplementary Materials**.

Incursion Scenarios

To examine the effectiveness of alternative approaches to incorporating vaccination into a control strategy across a range of starting conditions, we simulated control strategies for 13 incursion scenarios. Findings from the workshops and surveys were used to develop the characteristics of the incursion scenarios of interest to stakeholders. This included the method of FMD introduction, when FMD was introduced, type of source farm, time until first detection, and the reasons for selection of the scenarios. This approach ensured that the modeled outbreaks were relevant to the state and territory governments.

To convert inputs from stakeholder consultation into scenarios for the simulation study, we selected simulation runs based on stakeholders' scenario descriptions. A small set of up to 50 simulation runs was conducted for each incursion scenario at a time of year consistent with the scenario descriptions (as shown in **Table 2**). The simulation run that most resembled the description was used to identify the first infected farm, or "seed herd," for each incursion scenario. The selection was based on species, farm type, and geography of the starting location. Time until detection was fixed across incursion scenarios to focus comparisons on differences due to geographical conditions. A time of 21 days of silent spread before detection and disease control begins was chosen based on recent studies in Australia (6, 19, 20). The disease situation at detection (i.e., at the end of the silent spread phase of these representative runs) was saved as a "snapshot." **Figure 1** shows the locations of the seed herds for each of the 13 incursion scenarios.

The use of snapshots to capture the details of the incursion scenarios in AADIS ensured that alternative control strategies could be compared from an identical starting point when the disease was first detected, and control commenced.

TABLE 3 | Description of each control strategy in terms of approach to stamping out and targeting of vaccination.

Control strategy	Stamping out	Pre-emptive culling of DCPs%	Vaccination	Targeting of vaccination		
				Animals/Operations	Ring or Annulus	Area
1	Yes	No	No	–	–	–
2	Yes	Yes	No	–	–	–
3	Yes	No	Yes	All species*	5-km ring	All
4	Yes	No	Yes	All species	5-km ring	High-risk area#
5	Yes	No	Yes	All species except pigs and smallholders	5-km ring	All
6	Yes	No	Yes	Vaccination of specialist cattle producers^	5-km ring	All
7	Yes	No	Yes	Vaccination of specialist cattle producers^	5-km annulus, 5-km from IPs (out–in)	High-risk area#
8	Yes	No	Yes	Feedlots and large dairy farms >500 head	5-km annulus, 5-km from IPs (out–in)	All
9	Yes	Yes	Yes	All species	5-km ring	All

**Beef cattle on extensive properties were not targeted for vaccination in any control strategy because large extensive cattle properties are found only in northern Australia. They involve large areas with very low stocking densities and they are considered a low risk for FMD establishing/spreading. ^Including feedlots, dairy and intensive beef farms, but excluding extensive beef and mixed beef–sheep farms to avoid including large numbers of sheep on mixed farms in the vaccination program. #High-risk areas were defined as local government areas with high cattle herd densities and high cattle densities (>25 cattle per sq km). %DCPs are "Dangerous Contact Premises".*

TABLE 4 | Descriptive statistics for the Control Strategy 1 benchmark control strategy for all incursion scenarios.

Variable	Scenario	Mean	SD	Min	Max	p25	p50	p75	p95
Total number of IPs	NSW1	10	3	6	38	8	9	11	15
	NSW2	2	0	2	4	2	2	3	3
	NSW3	12	4	9	62	10	11	12	17
	QLD1	5	1	4	16	4	5	5	8
	QLD2	36	8	19	73	31	36	41	49
	QLD3	2	6	1	123	1	2	2	3
	SA1	5	1	3	17	5	5	6	7
	TAS1	2	1	2	5	2	2	3	4
	VIC1	2	0	2	3	2	2	2	2
	VIC2	872	690	218	5,593	528	734	1,046	1,511
	VIC3	128	225	30	3,291	72	91	116	226
	WA1	23	9	11	82	18	21	26	42
	WA2	15	3	10	63	13	14	15	18
Last day of control	NSW1	47	5	41	80	43	46	48	57
	NSW2	41	3	40	71	40	40	40	46
	NSW3	51	6	45	93	48	49	51	63
	QLD1	48	3	43	74	46	48	49	53
	QLD2	62	12	48	137	54	57	65	87
	QLD3	36	21	28	356	29	32	40	49
	SA1	48	6	44	86	45	45	49	63
	TAS1	47	3	42	75	45	46	48	51
	VIC1	39	0	39	40	39	39	39	39
	VIC2	223	82	112	718	175	207	249	348
	VIC3	124	61	59	609	92	109	136	201
	WA1	64	21	44	195	55	58	64	107
	WA2	51	4	45	83	48	50	52	60

Design of Control Strategies

For this study, nine control strategies were selected to provide a comparison of seven alternative approaches using vaccination with two benchmark control strategies with stamping out but no vaccination. Stamping out is the default approach for controlling an outbreak of FMD and aims to ensure infected premises are quarantined and that susceptible animals are destroyed to limit virus spread (3). For each incursion scenario, 500 simulation runs were conducted of each control strategy. Preliminary work has shown that this is adequate in providing a high degree of convergence (<5%) for key outbreak metrics (number of IPs, duration, and costs). Convergence provides an indication across a set of simulation runs to how close the sample mean of key "per-run indicators" is to the theoretical population mean (21).

Table 3 describes the main points of difference between the control strategies.

All control strategies included stamping out. Control Strategies 2 and 9 included the pre-emptive culling of DCPs. Control Strategies 3 to 9 included some form of vaccination in addition to stamping out. For all vaccination strategies, vaccination was triggered on day 14 of the control phase only if there were five or more infected premises (IPs), as it was considered unlikely that vaccination would be applied if there were only a small number of IPs. The approaches to vaccination differed in terms of the animal species and farm types targeted, whether a suppressive vaccination approach was used (5-km radius ring around an IP with vaccination from inside out) or a protective vaccination approach within an annulus (5 km wide starting 5 km away from an IP, i.e., in an area between 5 and 10 km from the IP, with vaccination occurring from the outside in) was used, and whether all areas were targeted or only herds in pre-identified high-risk, livestock-dense areas were targeted for vaccination. High-risk areas were defined as local government areas with high cattle herd density (>0.175 herds per sq km) and high cattle density (>25 cattle per sq km). Estimates of resource teams available to undertake control activities were provided by jurisdictional animal health staff and considered the availability of resources from both the public and private sectors. Details of the model settings and parameters are included in the **Supplementary Materials**.

Sensitivity Analysis

In addition to the baseline control strategies, sensitivity analyses were conducted to test how sensitive the results are to two key assumptions used in the study:

(a) Timing of vaccination—vaccination was assumed to start 14 days into the control program based on the expected time for vaccine to be available for deployment. To test the sensitivity

TABLE 5 | Descriptive statistics for Control Strategy 3 for all incursion scenarios.

Variable	Scenario	Mean	SD	Min	Max	p25	p50	p75	p95
Total number of IPs	NSW1	10	2	6	22	8	9	11	14
	NSW2	2	0	2	4	2	2	2	3
	NSW3	12	3	9	52	10	11	12	16
	QLD1	5	1	4	19	4	5	5	7
	QLD2	36	7	19	61	31	35	40	49
	QLD3	2	6	1	127	1	2	2	3
	SA1	5	2	3	30	5	5	6	7
	TAS1	2	1	2	10	2	2	3	4
	VIC1	2	0	2	3	2	2	2	2
	VIC2	221	52	127	807	191	214	243	292
	VIC3	64	16	35	176	54	61	71	94
	WA1	21	5	11	45	17	20	24	31
	WA2	15	3	11	53	13	14	15	19
Last day of control	NSW1	48	7	40	96	43	46	49	62
	NSW2	40	2	40	55	40	40	40	43
	NSW3	56	9	45	96	49	53	61	70
	QLD1	49	4	43	78	46	49	50	55
	QLD2	63	6	46	91	61	63	65	72
	QLD3	35	15	28	321	29	33	39	47
	SA1	48	7	44	87	45	45	49	65
	TAS1	47	4	42	90	46	47	48	51
	VIC1	39	1	39	50	39	39	39	39
	VIC2	99	17	73	225	90	96	106	125
	VIC3	72	11	56	144	65	68	77	95
	WA1	62	9	47	110	56	62	66	77
	WA2	54	8	45	93	48	52	60	68

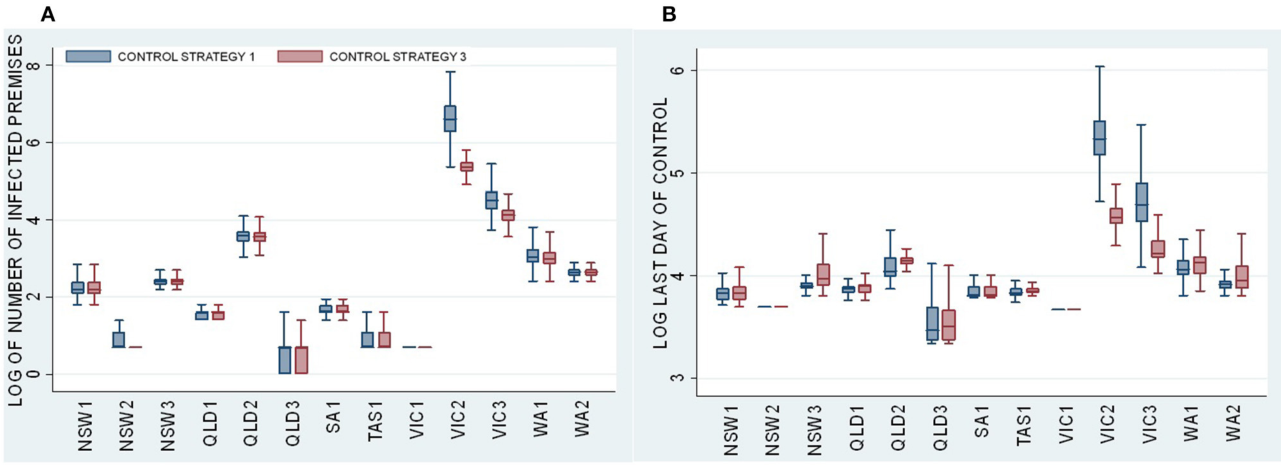


FIGURE 2 | Boxplots of **(A)** the log of total number of IPs and **(B)** the log of last day of control for the Control Strategy 1 stamping out strategy (blue) and the Control Strategy 3 vaccination strategy (red) for each incursion scenario.

TABLE 6 | Dunn tests on number of IPs.

Number of IPs		Comparisons between Control Strategies 2 to 9 and Control Strategy 1 (stamping out only)							
Incursion scenario	**Dunn test statistics**	**1 vs. 2**	**1 vs. 3**	**1 vs. 4**	**1 vs. 5**	**1 vs. 6**	**1 vs. 7**	**1 vs. 8**	**1 vs. 9**
NSW1	Statistics	**3.9634*** **	0.2847	−0.5694	−0.0694	−0.3014	0.0407	−0.8018	**5.4542*** **
NSW1	*p*-value	**0.0013**	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	**0.0000**
NSW2	Statistics	−0.2444	1.4432	0.3430	0.7574	0.4186	1.4809	0.8098	0.4711
NSW2	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
NSW3	Statistics	−0.4152	−0.8427	−0.1364	−0.2337	0.7346	−0.1541	−0.7765	−0.6992
NSW3	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
QLD1	Statistics	−0.5503	0.0942	0.3700	−0.3724	−0.4173	−0.6084	−0.3909	0.5117
QLD1	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
QLD2	Statistics	−2.2111	1.0125	0.7260	2.7675	2.1013	0.1648	0.2215	**3.1511** **
QLD2	*p*-value	0.4865	1.0000	1.0000	0.1017	0.6410	1.0000	1.0000	**0.0293**
QLD3	Statistics	−0.6188	−1.0859	−1.4378	1.8802	1.8277	0.4982	−0.0048	−0.6831
QLD3	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
SA1	Statistics	1.2517	0.3504	−0.3402	**2.9022***	−0.7021	0.7780	0.4911	1.0832
SA1	*p*-value	1.0000	1.0000	1.0000	**0.0667**	1.0000	1.0000	1.0000	1.0000
TAS1	Statistics	0.7128	1.4346	−0.0736	0.4477	0.1497	2.0318	0.3194	1.3158
TAS1	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	0.7592	1.0000	1.0000
VIC1	Statistics	−1.0145	−1.6814	0.3363	0.0000	−0.6754	−1.6906	−0.3425	0.6725
VIC1	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
VIC2	Statistics	0.6126	**30.6157*** **	**29.6603*** **	**30.1835*** **	**28.5593*** **	**20.9707*** **	**17.0234*** **	**31.5525*** **
VIC2	*p*-value	1.0000	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
VIC3	Statistics	1.1924	**18.7642*** **	**17.5880*** **	**17.5623*** **	**16.7609*** **	**9.3049*** **	**7.2829*** **	**19.7776*** **
VIC3	*p*-value	1.0000	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
WA1	Statistics	**4.6269*** **	**3.2538** **	1.3965	**3.1902** **	1.7224	1.6745	0.3430	**6.8012*** **
WA1	*p*-value	**0.0001**	**0.0205**	1.0000	**0.0256**	1.0000	1.0000	1.0000	**0.0000**
WA2	Statistics	**3.8885*** **	1.3583	0.3939	−0.1568	0.5833	1.6344	**2.7819***	**3.4730*** **
WA2	*p*-value	**0.0018**	1.0000	1.0000	1.0000	1.0000	1.0000	**0.0973**	**0.0093**

, **, * mean significant at $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively. The bold values are statistically significant values.*

of the results to timing of vaccination, vaccination programs starting on day 10 and day 21 were also simulated.

(b) Vaccination ring radius—based on stakeholder inputs, we assumed a 5-km ring vaccination radius. To test how sensitive the results are to the size of the vaccination ring, we also simulated a 3-km ring radius.

For the sensitivity analyses, the nine control strategies were run for each of the 13 incursion scenarios, with changed parameter values for these assumptions. Previous studies have conducted sensitivity analyses of other AADIS parameters, including time to detection and duration of the national standstill (16), and parameters relevant to FMD transmission, such as the probability of spread, infectivity, and susceptibility (22).

Statistical Analysis

The Kruskal–Wallis test was used to test whether there were differences in the mean number of IPs and the last day of control for each incursion scenario and control strategy combination. This test is a non-parametric analog to the ANOVA and was chosen as the appropriate test due to the data being non-normally distributed. The null hypothesis is that there are no significant differences in the median number of IPs and the last day of control for each of the control strategies, for each of the starting locations. The null hypothesis was rejected at the 95% confidence level. To examine specifically which control strategies and which incursion scenarios result in significant differences in the number of IPs and last day of control, we performed a Dunn test (23). The Dunn test is the appropriate non-parametric pairwise multiple comparison procedure when a Kruskal–Wallis test is rejected (24). We applied a Bonferroni adjustment to account for the number of pairwise comparisons conducted.

RESULTS

We compared alternative disease control strategies that incorporate vaccination with benchmark control strategies with stamping out only, across the range of incursion scenarios. We first present the results for the benchmark strategies, then the assessment of the effectiveness of vaccination based on a comprehensive ring vaccination approach (Control Strategy 3) for all incursion scenarios, before providing a more detailed analysis of the alternative types of vaccination strategy. Finally, we report the results of the sensitivity analyses.

Incursion Scenarios Derived From Stakeholder Consultation

Table 2 describes the starting conditions of each incursion scenario, including production type and number of animals

TABLE 7 | Dunn tests on last day of control.

Last Day of Control		Comparisons between Control Strategies 2 to 9 and Control Strategy 1 (stamping out only)							
Incursion scenario	Dunn test statistics	1 vs. 2	1 vs. 3	1 vs. 4	1 vs. 5	1 vs. 6	1 vs. 7	1 vs. 8	1 vs. 9
NSW1	Statistics	**−8.9822*** **	−0.6765	−0.1648	−0.6704	−1.3076	0.4781	−1.0602	**−10.8082*** **
NSW1	*p*-value	**0.0000**	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	**0.0000**
NSW2	Statistics	0.3989	2.1061	0.0786	0.9690	0.3778	1.2704	1.0085	−0.3777
NSW2	*p*-value	1.0000	0.6335	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
NSW3	Statistics	−0.2852	**−9.1792*** **	−1.0577	**−7.8178*** **	**−3.2603** **	−0.7075	−0.6496	**−8.9966*** **
NSW3	*p*-value	1.0000	**0.0000**	1.0000	**0.0000**	**0.0200**	1.0000	1.0000	**0.0000**
QLD1	Statistics	−2.5167	−2.6580	−0.7841	−2.1815	−2.7051	−2.0661	−1.8084	**−2.9727***
QLD1	*p*-value	0.2132	0.1415	1.0000	0.5246	0.1229	0.6987	1.0000	**0.0531**
QLD2	Statistics	**−3.3983** **	**−8.5038*** **	**−6.4720*** **	**−8.3998*** **	**−7.4976*** **	**−5.9211*** **	−1.0667	**−10.1058*** **
QLD2	*p*-value	**0.0122**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	1.0000	**0.0000**
QLD3	Statistics	−0.6267	−1.6059	−1.7620	0.7397	0.8837	0.0145	−1.2479	−0.8343
QLD3	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
SA1	Statistics	1.1272	−0.6250	−1.4629	1.4540	−1.0461	0.8012	0.6988	0.8665
SA1	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
TAS1	Statistics	0.4497	−0.5745	−0.3701	−0.4942	−0.5315	0.4408	−0.1987	0.3866
TAS1	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
VIC1	Statistics	−1.9164	−1.9033	0.0000	−0.3165	−0.9533	−1.9104	−0.3243	−1.2788
VIC1	*p*-value	0.9957	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
VIC2	Statistics	0.4837	**30.5759*** **	**28.9434*** **	**30.6717*** **	**26.7298*** **	**22.9713*** **	**16.4683*** **	**29.3161*** **
VIC2	*p*-value	1.0000	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
VIC3	Statistics	0.9270	**25.4775*** **	**25.7184*** **	**24.7720*** **	**23.4256*** **	**12.2731*** **	**7.9626*** **	**22.7966*** **
VIC3	*p*-value	1.0000	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
WA1	Statistics	1.3173	**−4.5509*** **	2.4955	**−5.6252*** **	−1.8958	2.7270	1.8492	**−5.3097*** **
WA1	*p*-value	1.0000	**0.0001**	0.2264	**0.0000**	1.0000	0.1150	1.0000	**0.0000**
WA2	Statistics	1.0975	**−5.4508*** **	−0.1338	**−5.9318*** **	**−6.8597*** **	0.6469	0.6700	**−5.4624*** **
WA2	*p*-value	1.0000	**0.0000**	1.0000	**0.0000**	**0.0000**	1.0000	1.0000	**0.0000**

, **, * mean significant at $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively. The bold values are statistically significant values.*

in each seed herd and the number of infected herds in the population for each snapshot, that is, when the outbreak is first detected, and the control program begins.

Benchmark Strategies for All Incursion Scenarios

For comparison with alternative approaches using vaccination, simulations were conducted with a benchmark strategy of stamping out only (Control Strategy 1) and stamping out with pre-emptive culling of DCPs (Control Strategy 2). **Tables 4**, **5** present descriptive statistics for all incursion scenarios for the benchmark, Control Strategy 1, for the total number of IPs and the last day of control (i.e., duration of the control program).

The last day of control measures the number of days of disease control as the number of days of culling plus two incubation periods (28 days). For many of the incursion scenarios, the outbreaks were small and controlled relatively quickly. The Victorian scenarios VIC2 and VIC3 were the largest, followed by WA1, a scenario in Western Australia. In particular, the VIC2 outbreak could become very large and potentially last more than 12 months.

The pre-emptive culling of DCPs is an additional control measure that could be considered to help contain and manage the outbreak. In this study, Control Strategy 2 allows comparison with Control Strategy 9, which combines vaccination with the pre-emptive culling of DCPs.

Comparing the strategies of stamping out only (Control Strategy 1) and stamping out with pre-emptive culling of DCPs (Control Strategy 2) using Dunn tests, we found that there were statistically significant differences in the total number of IPs for incursion scenarios NSW1, WA1, and WA2 and in the last day of control for NSW1 and QLD2. The differences between the medians, however, are small and do not appear important for disease control. Notably, no statistically significant differences were found between Control Strategy 1 and Control Strategy 2 for the two incursion scenarios with the largest outbreaks, i.e., VIC2 and VIC3.

The Effect of Vaccination on Outbreak Size and Duration

Descriptive statistics and Dunn test statistics were used to compare the effect of the vaccination strategy across all 13

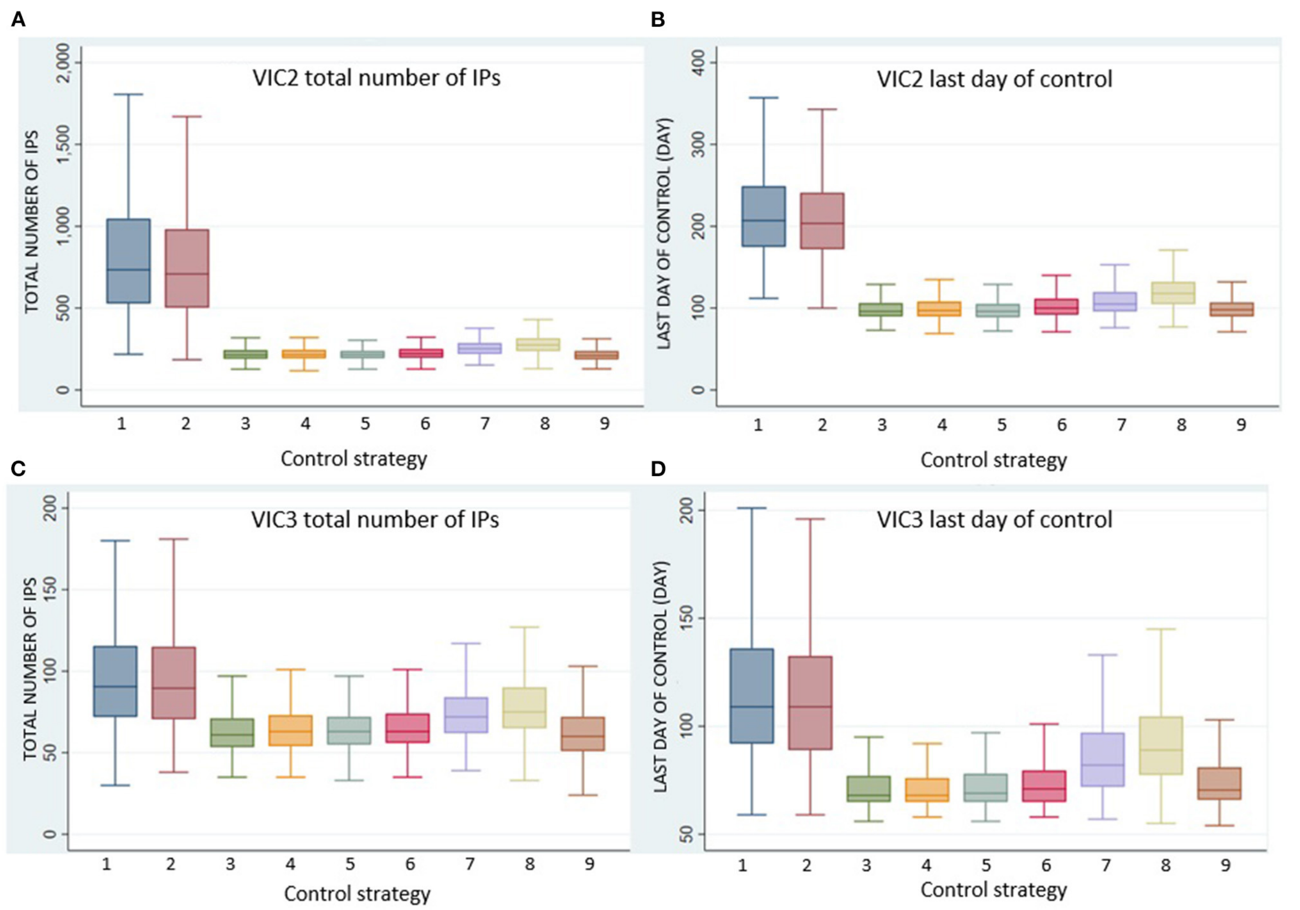


FIGURE 3 | Boxplots of **(A)** VIC2 total number of IPs, **(B)** VIC2 last day of control, **(C)** VIC3 total number of IPs, and **(D)** VIC3 last day of control for each control strategy, Control Strategy 1 to Control Strategy 9.

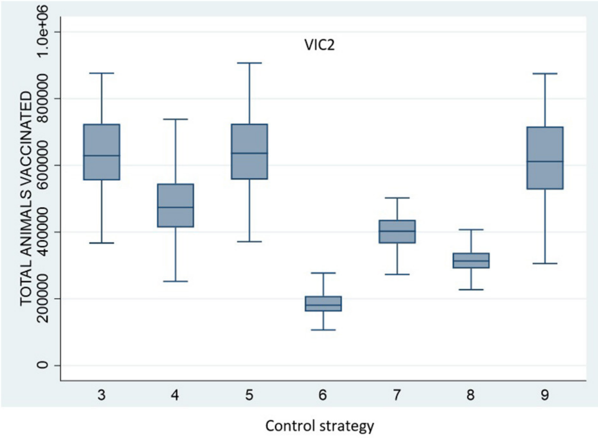


FIGURE 4 | Boxplots of the total number of vaccinated animals for Scenario VIC2 for the control strategies with vaccination (Control Strategy 3 to 9).

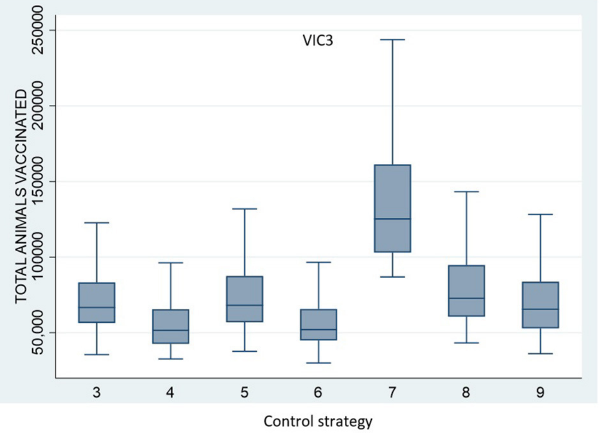


FIGURE 5 | Boxplots of the total number of vaccinated animals for Scenario VIC3 for the control strategies with vaccination (Control Strategy 3 to 9).

incursion scenarios by comparing a stamping out only (Control Strategy 1) with a comprehensive vaccination strategy (Control Strategy 3), which involves vaccinating all species in a 5-km radius of each infected premises. **Figure 2** presents boxplots of the distributions of (a) the total number of IPs and (b) the last day of control across all 500 iterations for Control Strategies 1 and 3. For each incursion scenario, NSW1 to WA3, **Figure 2** shows boxplots for Control Strategy 1 on the left and Control Strategy 3 on the right.

Figure 2 presents the log of the size and duration of all the outbreaks. Most of the incursion scenarios shown in **Figure 2** lead to small outbreaks that are controlled relatively quickly by Control Strategy 1. Vaccination (Control Strategy 3) offers no benefits in terms of reducing the size of the outbreak (number of IPs) or duration. Note that there is very little difference in the size and duration of the smaller outbreaks (NSW1–NSW3, QLD1–QLD3, SA1, TAS1, VIC1, WA1, and WA2) between Control Strategy 1—stamping out only (blue) and Control Strategy 3—vaccination strategy (red). A Dunn test statistic confirms that there are no significant differences in the median value of the total number of IPs and last day of control between Control Strategy 1 and Control Strategy 3 for all incursion scenarios shown in **Figure 2**.

However, in the case of Victorian scenarios (VIC2 and VIC3), the outbreaks are larger. In these cases, vaccination is effective in reducing the size and duration of the outbreaks. There is a marked contrast between the median of 734 for the total number of IPs for the VIC2-Control Strategy 1 (stamping out only) and the median of 214 for the VIC2-Control Strategy 3 (stamping out with vaccination). The same pattern holds for VIC3, with a median of 91 IPs for VIC3-Control Strategy 1 compared with 61 for VIC3-Control Strategy 3. Although only Control Strategy 3 is presented in **Figure 2**, Dunn tests comparing every vaccination strategy (Control Strategy 3 to Control Strategy 9) with Control Strategy 1 showed similar effects (see **Tables 6**, **7**).

Alternative Vaccination Strategies and the Size and Duration of Large Outbreaks

Here, we focused on comparing the seven alternative vaccination approaches (Control Strategy 3 to Control Strategy 9) with the benchmark stamping out approaches (Control Strategy 1 and Control Strategy 2) for the two incursion scenarios in Victoria, VIC2 and VIC3, which were associated with larger outbreak sizes and for which vaccination was shown to be very effective in reducing size and duration of the outbreaks. VIC2 begins in a dairy herd in southwest Victoria, and VIC3 begins in an intensive beef property in southeast Victoria (see **Table 2** and **Figure 1**). **Figure 3** compares the effect of the different vaccination strategies on outbreak size and duration.

All vaccination strategies were effective in reducing outbreak size and duration. However, Control Strategy 7 and Control Strategy 8 (the annulus strategies) were less effective than the ring vaccination strategies. Additionally, there was little difference in outbreak size and duration for Control Strategies 3, 4, 5, and 6. There were significant differences, however, in the numbers of animals vaccinated under the different strategies. The total number of vaccinated animals is shown for each vaccination strategy for scenario VIC2 in **Figure 4** and for scenario VIC3 in **Figure 5**. **Tables 8**, **9** present the results of the Dunn test of statistical differences comparing these strategies.

Control Strategy 6 consistently performed well in this study. This strategy applies vaccination to specialist cattle producers within a 5-km radius around each IP, including feedlots and dairy and intensive beef farms, but excluding mixed beef–sheep farms to avoid including large numbers of sheep on mixed farms in the vaccination program. Note that for Control Strategy 8, very few farms met the stringent criteria to be vaccinated. For example, under scenario VIC2, the median number of premises being vaccinated per run was only 1 (range 0–8).

Figure 6 presents the proportions of the simulation runs for each incursion scenario where the vaccination trigger of five or more infected premises on day 14 of the control phase was met (out of 500 simulations runs for Control Strategy 3).

TABLE 8 | Dunn test of total animals vaccinated for Scenario VIC2.

Control strategies	Dunn test statistics	Control strategies					
		3	4	5	6	7	8
4	Statistics	**12.8766**					
	p-value	**0.0000*** **					
5	Statistics	−0.08046	**−1.30E + 01**				
	p-value	1.0000	**0.0000*** **				
6	Statistics	**38.0533**	**25.1767**	**38.1338**			
	p-value	**0.0000*** **	**0.0000*** **	**0.0000*** **			
7	Statistics	**20.6108**	**7.7342**	**20.6912**	**−1.74E + 01**		
	p-value	**0.0000*** **	**0.0000*** **	**0.0000*** **	**0.0000*** **		
8	Statistics	**29.3102**	**16.4336**	**29.3907**	**−8.7431**	**8.6995**	
	p-value	**0.0000*** **	**0.0000*** **	**0.0000*** **	**0.0000*** **	**0.0000*** **	
9	Statistics	1.6069	**−1.13E + 01**	1.6873	**−3.64E + 01**	**−1.90E + 01**	**−2.77E + 01**
	p-value	1.0000	**0.0000*** **	0.9612	**0.0000*** **	**0.0000*** **	**0.0000*** **

, **, * mean significant at $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively. The bold values are statistically significant values.*

TABLE 9 | Dunn test of total animals vaccinated for Scenario VIC3.

Control strategies	Dunn test statistics	Control strategies					
		3	4	5	6	7	8
4	Statistics	**10.8898**					
	p-value	**0.0000*** **					
5	Statistics	−1.0787	**−1.20E + 01**				
	p-value	1.0000	**0.0000*** **				
6	Statistics	**10.1952**	−0.6946	**11.2739**			
	p-value	**0.0000*** **	1.0000	**0.0000*** **			
7	Statistics	**−2.12E + 01**	**−3.21E + 01**	**−2.01E + 01**	**−3.14E + 01**		
	p-value	**0.0000*** **	**0.0000*** **	**0.0000*** **	**0.0000*** **		
8	Statistics	**−4.3208**	**−1.52E + 01**	**−3.2421**	**−1.45E + 01**	**16.8406**	
	p-value	**0.0002*** **	**0.0000*** **	**0.0125** **	**0.0000*** **	**0.0000*** **	
9	Statistics	1.5089	**−9.3809**	2.5876	**−8.6863**	**22.6704**	**5.8298**
	p-value	1.0000	**0.0000*** **	0.1015	**0.0000*** **	**0.0000*** **	**0.0000*** **

, **, * mean significant at $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively. The bold values are statistically significant values.*

It is worth noting that for Control Strategy 3, vaccination was triggered in 7 of the 13 scenarios (NSW1, NSW3, QLD3, VIC2, VIC3, WA1, and WA2). On the other hand, there were four scenarios where vaccination was never triggered (NSW2, QLD3, TAS1, and VIC1). Vaccination was never triggered in these scenarios because there were fewer than five IPs on Day 14 of the control phase.

Results of Sensitivity Analyses

Sensitivity analysis around the assumptions of the timing of vaccination (day 10 vs. day 21 vs. baseline day 14) and vaccination ring radius (3 km vs. baseline 5 km) suggests that results are robust to changes in the assumptions around vaccination. **Table 10** presents the Dunn test results for the assumptions of the timing of vaccination (day 10 vs. day 21) and vaccination ring radius (3 km vs. baseline 5 km).

DISCUSSION AND CONCLUSION

This paper shows the results of a simulation study informed by stakeholder consultation that investigated options for incorporating vaccination into control strategies for FMD outbreaks across Australia, including areas considered to be at lower risk for introduction and spread of FMD.

For previously FMD-free countries, FMD control has tended to be based on stamping out and indeed this is Australia's preferred approach as described in AUSVETPLAN (3). However, the use of vaccination in control of an FMD outbreak is increasingly recognized as an important option (9, 25, 26). This is driven by resourcing issues and ethical, environmental, and welfare concerns over the large-scale culling of animals (5, 25, 27–30). While vaccination may contribute to earlier eradication of the disease, it will be associated with additional costs—keeping vaccinated animals in the population will delay the period until

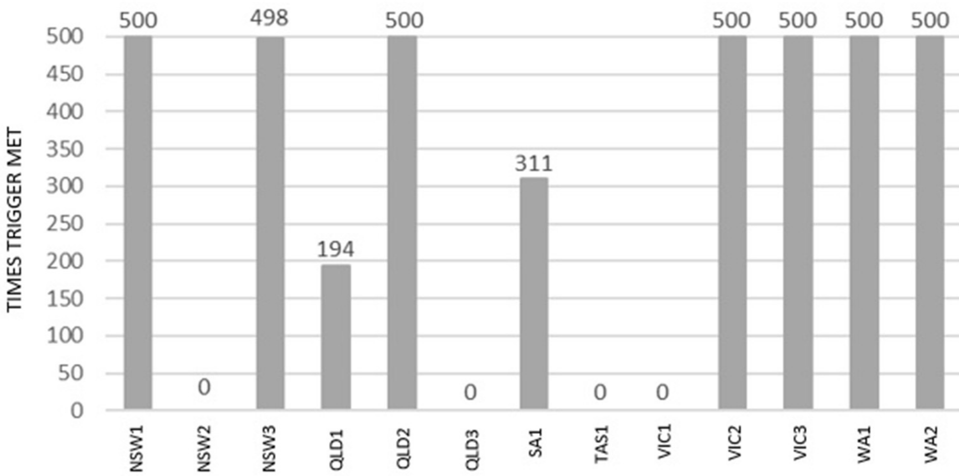


FIGURE 6 | Number of simulations the vaccination trigger was met during 500 simulations of Control Strategy 3 for each incursion scenario.

TABLE 10 | Dunn tests for sensitivity analyses—comparisons of Control Strategy 1 with Control Strategy 3 for baseline simulation assumptions and changed vaccination assumptions for sensitivity analysis.

Variable	Incursion scenario	Dunn test statistics	Baseline simulations	Sensitivity analysis simulations with changed assumptions		
			(B) Day 14/5 km	(1) Day 14/3 km	(2) Day 10/5 km	(3) Day 21/5 km
			Control Strategy 1 vs. 3	Control Strategy 1 vs. 3	Control Strategy 1 vs. 3	Control Strategy 1 vs. 3
Number of IPs	VIC2	Statistics	31.5108	20.6578	24.5240	23.0540
	VIC2	*p*-value	0.0000***	0.0000***	0.0000***	0.0000***
Last day of control	VIC2	Statistics	31.1772	18.4195	23.8080	27.0068
	VIC2	*p*-value	0.0000***	0.0000***	0.0000***	0.0000***
Number of IPs	VIC3	Statistics	25.0053	22.3874	20.7088	18.4084
	VIC3	*p*-value	0.0000***	0.0000***	0.0000***	0.0000***
Last day of control	VIC3	Statistics	18.3969	16.5565	17.4394	12.4666
	VIC3	*p*-value	0.0000***	0.0000***	0.0000***	0.0000***

(B) Baseline assumption: vaccination from Day 14 and 5-km vaccination ring radius.
(1) Alternative: vaccination from Day 14 and 3-km vaccination ring radius.
(2) Alternative: vaccination from Day 10 and 5-km vaccination ring radius.
(3) Alternative: vaccination from Day 21 and 5-km vaccination ring radius.
, **, * mean significant at $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively.*

FMD-free status is regained under current World Organization for Animal Health standards (13, 31) and add additional complexity to post-outbreak surveillance programs (32).

This analysis has shown that many outbreaks of FMD in Australia, based on incursion scenarios identified by stakeholders, were comparatively small. Management through stamping out without vaccination may be the most appropriate response for these smaller outbreaks, as vaccination did not reduce the size or duration and the cost of vaccination may increase control costs substantially. The largest simulated outbreaks were observed for two Victorian incursion scenarios (VIC2 and VIC3). This is consistent with previous work that identified southeastern Australia as the area most vulnerable to an FMD outbreak because of its geographic and climatic conditions, including its relatively high human population and its higher stocking rates (20). In Victoria, the temperature, climate, and higher rainfall mean that there is more intensive farming than in most other parts of Australia.

For the large simulated outbreaks in Victoria, vaccination was shown to reduce both the size (total number of IPs) and length of an outbreak. This finding is also consistent with previous modeling studies in Australia (4, 5, 28) and overseas (9, 25, 26, 33–36), which found that vaccination can be an effective strategy in suppressing the spread of infection particularly if livestock density is high, disease is widespread, there is a high rate of spread, or resources for stamping out are limited.

Suppressive ring vaccination, that is, vaccinating in a ring immediately around IPs, was found to be more effective than vaccination in an annulus, further out from the IPs. A previous study using multiple models and a United Kingdom outbreak scenario also concluded that suppressive ring vaccination was a more effective use of vaccine resources (5). A similar impact on outbreak size and duration was found regardless of the approach to ring vaccination (Control Strategies 3–6). However, there were significant differences in the numbers of animals vaccinated under the different strategies. Vaccinating cattle only was particularly effective. In their multi-model study, Roche et al. (9) reported that a cattle-only vaccination strategy was as effective as vaccinating all susceptible species for three of the four models used in their study.

Issues with management of vaccinated animals following an FMD outbreak and trade restrictions have limited the use of vaccination as a first-line control strategy, especially for countries with large export industries. FMD-free status can be recovered 3 months after the last reported case under stamping-out or pre-emptive culling strategies, and this increases to 6 months when vaccination is used unless all vaccinated animals are removed from the population, in which case free status can be regained 3 months after removing the vaccinated animals (13). To minimize duration of the closure of export markets, under current international standards, vaccinated animals would need to be removed from the population (31). However, culling vaccinated animals obviously has additional animal welfare, economic, and social impacts. In this situation, it would be desirable to minimize the number of animals vaccinated while still achieving effective control. This study and others [e.g., (9)] confirm that selective, targeted vaccination can be an effective strategy to reduce the number of animals vaccinated. We found that targeting vaccination to high-risk areas (strategy Control Strategy 4) or to cattle only (Control Strategy 6) achieved effective control of the large Victorian outbreak scenarios, while significantly reducing the number of animals vaccinated compared to more expansive vaccination strategies.

Given the finding that vaccination when used with stamping can be very effective in reducing the size and duration of large outbreaks compared to stamping out on its own, a key issue is deciding when it should be used. That is, how can decision makers identify situations when an outbreak is likely to be large. A decision to vaccinate early in the outbreak may result in situations where it was not actually required and have consequent implications for post-outbreak surveillance, management of vaccinated animals, and regaining FMD-free status and access to export markets (31, 32). Conversely, not using vaccination in some situations may lead to much larger and longer outbreaks, increased control costs, and greater impacts on industry and local communities (6). During an outbreak, decisions on control are often made under significant uncertainty and in conditions that are continually evolving. Resources are often limited and will influence the effectiveness of disease control efforts. The decision to vaccinate and choice of strategy will ultimately depend on the nature of the epidemic, available resources to implement it, and objectives of the control program [(37); also see AUSVETPLAN, (3)]. Work by Hutber et al. (38), Halasa et al. (39), and Sarandopoulos (40) indicates that information available early in an outbreak can be used to make inferences about the potential severity of an FMD outbreak. In a detailed study involving simulated FMD outbreaks in Australian and New Zealand, Garner et al. (6) showed that relatively simple metrics that would be available to disease managers early in an outbreak such as the cumulative number of IPs were consistently found to be strongly associated with the final size and the duration of the outbreak.

There are two key implications from these findings. First, combining stakeholder consultation to formulate scenarios and strategies for epidemiological modeling revealed that many incursion scenarios of concern to stakeholders in Australia are likely to lead to small outbreaks. These outbreaks could be managed effectively with stamping out alone and is consistent with findings in other low livestock density situations (33). This highlights the importance of incorporating the views and expertise of stakeholders in scenario formulation and not just focusing on large, worst-case scenarios when comparing control strategies. Stakeholder consultation helped identify the concerns and priorities of disease managers across the Australian jurisdictions and ensured that the simulations were driven by decision-makers' needs rather than just the possibilities of the modeling platform.

Second, notwithstanding the effectiveness of vaccination to reduce the size and duration of large outbreaks, under current international standards (13), there remains a strong disincentive to use vaccination under the belief that a vaccination policy will always result in the longest return to markets for exports of susceptible livestock and their products. To minimize trade impacts, vaccinated animals need to be removed from the population at the end of the outbreak. Given this situation, we have shown that targeted vaccination strategies are effective in achieving control while reducing the numbers of animals vaccinated. Differential time periods are being challenged (41) and new diagnostic approaches that improve surveillance might be able to provide acceptable levels of confidence in the infection status of vaccinated populations in the future.

Future research could further investigate and validate the effectiveness of vaccination as a control strategy for FMD. We suggest analysis to determine whether vaccination can reduce the probability of extremely large and long outbreaks. In this study, the focus was on the median size and duration of an outbreak. Examining the effect of alternative control strategies on the probability of large and long outbreaks will provide decision makers with a better understanding of the potential role of vaccination. An additional area for further work also includes spatially and temporally mapping the risk of FMD spread to help identify regions where vaccination is more likely to play a useful role. More comprehensive modeling studies could be used to assess which areas may be more vulnerable or susceptible to large outbreaks. Further work to refine early decision indicators of severe outbreaks to support decision-making is important. Lastly, we recommend further research to investigate the trade-offs between the cost of using vaccination as a control strategy and the effectiveness of the outcome. The costs should include consideration of direct costs of the control strategies and indirect costs, such as revenue loss from animal movement restrictions, loss from trade embargoes, and the cost of business recovery and continuity after eradication. The effectiveness of the outcome should be considered not only in terms of infected premises and control duration but also in terms of numbers of animals vaccinated and culled. This could consider the ethical, welfare, and social benefits of reducing culling using vaccination.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by CSIRO Human Ethics research committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

TC: project lead and main author of manuscript writing. MG: epidemiological modeling and write up of methods and results. ST: statistical analysis and write up of methods and results. SR and SL: stakeholder consultation design and implementation. CM, ACB, and SH: provided input toward conceptual model and analysis of results. All authors contributed to the article and approved the submitted version.

FUNDING

This project was supported by Meat & Livestock Australia (MLA), through funding from the Australian Government Department of Agriculture, Water and the Environment as part of its Rural R&D for Profit program, and by producer levies from Australian FMD-susceptible livestock (cattle, sheep, goats and pigs) industries and Charles Sturt University (CSU), leveraging significant in-kind support from the research partners. The research partners for this project were the Commonwealth Science and Industrial Research Organization (CSIRO), CSU through the Graham Center for Agricultural Innovation, and the Bureau of Meteorology (BOM) and the Australian Department of Agriculture, Water and the Environment, supported by Animal Health Australia (AHA).

ACKNOWLEDGMENTS

We would like to acknowledge the important roles played by Kathy Gibson, Sarika Pandya, Francette Geraghty-Dusan, and others at Animal Health Australia, Ahmed Hafi and Donkor Addai at ABARES, Louise Sharp at the Department of Agriculture, Water and the Environment, Wilna Vosloo and Ann Seitzinger at CSIRO, and Florence Wang, Louise Ord, and others at CSIRO IM&T Scientific Computing. We would also like to acknowledge the contributions of three interns who worked on student projects related to the project, Elsa Schalck, Julie Pinol, and Manon Courias. This project has also benefited from numerous contributions from many government and industry representatives who have generously contributed their knowledge and experience as inputs into this research.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.648003/full#supplementary-material

REFERENCES

1. Matthews K. A review of Australia's preparedness for the threat of foot-and-mouth disease. In: *Australian Government Department of Agriculture*, *F. A. F. (ed.)*. Canberra: ACT (2011). Available online at: https://www.agriculture.gov.au/pests-diseases-weeds/animal/fmd/review-foot-and-mouth-disease (accessed May 7, 2021).
2. Buetre B, Wicks S, Kruger H, Millist N, Yainshet A, Garner G, et al. *Potential Socio-Economic Impacts of an Outbreak of Foot-and-Mouth Disease in Australia*. Australian Bureau of Agricultural and Resource Economics and Sciences research report 13.11 (2013). Available online at: https://www.agriculture.gov.au/sites/default/files/abares/documents/RR13.11PotSocEcoImpctOfFMD_v1.0.0.pdf (accessed July 26, 2021).
3. Animal Health Australia. *Disease strategy: Foot-and-mouth disease (Version 3.4). Australian Veterinary Emergency Plan (AUSVETPLAN), Edition 3, Agriculture Ministers' Forum*. Canberra: ACT. Available online at: https://www.animalhealthaustralia.com.au/our-publications/ausvetplan-manuals-and-documents (accessed May 7, 2021).
4. Abdalla A, Beare S, Cao L, Garner G, Heaney A. *Foot and Mouth: Evaluating Alternatives for Controlling Disease Outbreaks*. ABARE Report 05.6. Canberra: Australian Bureau of Agricultural and Resource Economics (2005).
5. Roche SE, Garner MG, Wicks RM, East IJ, De Witte K. How do resources influence control measures during a simulated outbreak of foot and mouth disease in Australia? *Prevent Vet Med*. (2014) 113:436–46. doi: 10.1016/j.prevetmed.2013.12.003
6. Garner MG, East IJ, Stevenson MA, Sanson RL, Rawdon TG, Bradhurst RA, et al. Early decision indicators for foot-and-mouth disease outbreaks in non-endemic countries. *Front Vet Sci.* (2016) 3:109. doi: 10.3389/fvets.2016.00109
7. Tomassen FHM, De Koeijer A, Mourits MCM, Dekker A, Bouma A, Huirne RBM. A decision-tree to optimise control measures during the early stage of a foot-and-mouth disease epidemic. *Prevent Vet Med.* (2002) 54:301–24. doi: 10.1016/S0167-5877(02)00053-3
8. Keeling M, Woolhouse M, May R, Davies G, Grenfell B. Modelling vaccination strategies against foot-and-mouth disease. *Nature.* (2003) 421:136–42. doi: 10.1038/nature01343
9. Roche SE, Garner MG, Sanson RL, Cook C, Birch C, Backer JA, et al. Evaluating vaccination strategies to control foot-and-mouth disease: a model comparison study. *Epidemiol Infect.* (2015) 143:1256–75. doi: 10.1017/S0950268814001927
10. Sakamoto K. Mechanism of FMD outbreaks and its control in Asian region. *J Disast Res.* (2012) 7:258–63. doi: 10.20965/jdr.2012.p0258
11. Muroga N, Hayama Y, Yamamoto T, Kurogi A, Tsuda T, Tsutsui T. The 2010 Foot-and-mouth disease epidemic in Japan. *J Vet Med Sci.* (2012) 74:399–404. doi: 10.1292/jvms.11-0271
12. Nishiura H, Omori R. An epidemiological analysis of the foot-and-mouth disease epidemic in Miyazaki, Japan, 2010. *Transbound Emerg Dis.* (2010) 57:396–403. doi: 10.1111/j.1865-1682.2010.01162.x
13. OIE. *Chapter 1.11 Application for Official Recognition by the OIE of Free Status for Foot and Mouth Disease*. Terrestrial Animal Health Code. 28th Edition. Paris: OIE (2019).

14. Garner MG, Hamilton SA. Principles of epidemiological modelling. *Rev Sci Tech*. (2011) 30:407–16. doi: 10.20506/rst.30.2.2045
15. Animal Health Australia. *Foot-and-mouth Disease Vaccine Management*. Available online at: https://www.animalhealthaustralia.com.au/what-we-do/emergency-animal-disease/foot-and-mouth-disease-vaccine-management (accessed May 7, 2021).
16. Bradhurst RA, Roche SE, East IJ, Kwan P, Garner MG. A hybrid modeling approach to simulating foot-and-mouth disease outbreaks in Australian livestock. *Front Environ Sci*. (2015) 3:17. doi: 10.3389/fenvs.2015.00017
17. Australian Bureau of Statistics. *Agricultural Commodities, Australia (cat. no. 7121.0)*. (2011). Available online at: https://www.abs.gov.au/ausstats/abs@.nsf/Lookup/7121.0main+features82011-12 (accessed July 23, 2021).
18. Bradhurst R, Roche S, East I, Kwan P, Garner G. Improving the computational efficiency of an agent-based spatiotemporal model of livestock disease spread and control. *Environ Model Softw*. (2016) 77:1–12. doi: 10.1016/j.envsoft.2015.11.015
19. Martin P, Langstaff I, Iglesias R, East I, Sergeant E, Garner M. Assessing the efficacy of general surveillance for detection of incursions of livestock diseases in Australia. *Prev Vet Med*. (2015) 121:215–30. doi: 10.1016/j.prevetmed.2015.06.017
20. East IJ, Martin PAJ, Langstaff I, Wicks RM, Sergeant ESG, Garner MG, et al. Assessing the delay to detection and the size of the outbreak at the time of detection of incursions of foot and mouth disease in Australia. *Prev Vet Med*. (2015) 123:1–11. doi: 10.1016/j.prevetmed.2015.12.005
21. Driels MR, Shin YS. *Determining the Number of Iterations for Monte Carlo Simulations of Weapon Effectiveness (No. NPS-MAE-04-005)*. Naval Postgraduate School, Monterey California, Department of Mechanical and Astronomical Engineering (2004). Available online at: https://calhoun.nps.edu/handle/10945/798 (accessed July 26, 2021).
22. Bradhurst RA. *Modelling the Spatiotemporal Spread and Control of Viral Disease in Livestock Using a Hybrid Equation-Based and Agent-Based Approach*. PhD Thesis, University of New England (2015). Available online at: https://hdl.handle.net/1959.11/19661 (accessed July 26, 2021).
23. Dunn OJ. Multiple comparisons using rank sums. *Technometrics*. (1964) 6:241–52. doi: 10.1080/00401706.1964.10490181
24. Dinno A. Nonparametric pairwise multiple comparisons in independent groups using Dunn's test. *Stata J*. (2015) 15:292–300. doi: 10.1177/1536867X1501500117
25. Backer JA, Hagenaars TJ, Nodelijk G, van Roermund HJW. Vaccination against foot-and-mouth disease I: epidemiological consequences. *Prevent Vet Med*. (2012) 107:27–40. doi: 10.1016/j.prevetmed.2012.05.012
26. Boklund A, Halasa T, Christiansen LE, Enøe C. Comparing control strategies against foot-and-mouth disease: will vaccination be cost effective in Denmark? *Prevent Vet Med*. (2013) 111:206–19. doi: 10.1016/j.prevetmed.2013.05.008
27. Garner MG, Dubé C, Stevenson MA, Sanson RL, Estrada C, Griffin J. Evaluating alternative approaches to managing animal disease outbreaks – the role of modelling in policy formulation. *Vet Ital*. (2007) 43:285–98.
28. Garner MG, Bombarderi N, Cozens M, Conway ML, Wright T, Paskin R, et al. Estimating resource requirements to staff a response to a medium to large outbreak of foot and mouth disease in Australia. *Transbound Emerg Dis*. (2016) 63:e109–21. doi: 10.1111/tbed.12239
29. Laurence CJ. Animal welfare consequences in England and Wales of the 2001 epidemic of foot and mouth disease. *Rev Sci Tech*. (2002) 21:863–8. doi: 10.20506/rst.21.3.1382
30. Pluimers FH, Akkerman AM, van der Wal P, Dekker A, Bianchi A. Lessons from the foot and mouth disease outbreak in the Netherlands 2001. *Rev Sci Tech*. (2002) 21:711–21 doi: 10.20506/rst.21.3.1371
31. Bradhurst R, Garner G, East I, Death C, Dodd A, Kompas T. Management strategies for vaccinated animals after an outbreak of footand-mouth disease and the impact on return to trade. *PLoS ONE*. (2019) 14:e0223518. doi: 10.1371/journal.pone.0223518
32. Bradhurst R, Garner G, East I, Death C, Dodd A, Kompas T. Post-outbreak surveillance strategies to support proof-of-freedom from foot-and-mouth disease. *bioRxiv:2021.2004.2027.441714*. (2021). doi: 10.1101/2021.04.27.441714
33. Dürr S, Fasel-Clemenz C, Thür B, Schwermer H, Doherr MG, zu Dohna H, et al. Evaluation of the benefit of emergency vaccination in a foot-and-mouth disease free country with low livestock density. *Prevent Vet Med*. (2014) 113:34–46. doi: 10.1016/j.prevetmed.2013.10.015
34. Porphyre T, Auty HK, Tildesley MJ, Gunn GJ, Woolhouse MEJ. Vaccination against foot-and-mouth disease: do initial conditions affect its benefit? *PLoS ONE*. (2013) 8:e77616. doi: 10.1371/journal.pone.0077616
35. Miller G, Gale SB, Eshelman CE, Wells SJ. Emergency vaccination use in a modelled foot and mouth disease outbreak in Minnesota. *Rev Sci Tech*. (2015) 34:729–40. doi: 10.20506/rst.34.3.2392
36. Tildesley MJ, Savill NJ, Shaw DJ, Deardon R, Brooks SP, Woolhouse MEJ, et al. Optimal reactive vaccination strategies for a foot-and-mouth outbreak in the UK. *Nature*. (2006) 440:83–6. doi: 10.1038/nature04324
37. ProbertWJM, Shea K, Fonnesbeck CJ, Runge MC, Carpenter TE, Dürr S, et al. Decision-making for foot-and-mouth disease control: objectives matter. *Epidemics*. (2015) 15:10–9. doi: 10.1016/j.epidem.2015.11.002
38. Hutber A, Kitching R, Pilipcinec E. Predictions for the timing and use of culling or vaccination during a foot-and-mouth disease epidemic. *Res Vet Sci*. (2006) 81:31–6. doi: 10.1016/j.rvsc.2005.09.014
39. Halasa T, Willeberg P, Christiansen L, Boklund A, Alkhamis M, Perez A, et al. Decisions on control of foot-and-mouth disease informed using model predictions. *Prev Vet Med*. (2013) 112:194–202. doi: 10.1016/j.prevetmed.2013.09.003
40. Sarandopoulos J. *Early Predictors of the Size and Duration of Foot-and Mouth Disease Epidemics*. Unpublished Bachelor of Science Honours Thesis. Melbourne, Australia: Faculty of Veterinary and Agricultural Sciences, University of Melbourne (2015).
41. Geale DW, Barnett PV, Clarke GW, Davis J, Kasari TR. A review of OIE country status recovery using vaccinate-to-live versus vaccinate-to-die foot-and-mouth disease response policies II: waiting periods after emergency vaccination in FMD free countries. *Transbound Emerg Dis*. (2015) 62:388–406. doi: 10.1111/tbed.12165

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.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 08 October 2021
doi: 10.3389/fvets.2021.644009

Check for updates

Estimating the Economic Loss Due to Vibriosis in Net-Cage Cultured Asian Seabass (*Lates calcarifer*): Evidence From the East Coast of Peninsular Malaysia

*Siti Hajar Mohd Yazid[1], Hassan Mohd Daud[2,3], Mohammad Noor Amal Azmai[3,4], Nurliyana Mohamad[4,5] and Norhariani Mohd Nor[1,3]**

[1] Department of Veterinary Preclinical Sciences, Faculty of Veterinary Medicine, Universiti Putra Malaysia, Serdang, Malaysia, [2] Department of Veterinary Clinical Studies, Faculty of Veterinary Medicine, Universiti Putra Malaysia, Serdang, Malaysia, [3] Aquatic Animal Health and Therapeutics Laboratory, Institute of Bioscience, Universiti Putra Malaysia, Selangor, Malaysia, [4] Department of Biology, Faculty of Science, Universiti Putra Malaysia, Serdang, Malaysia, [5] Department of Aquaculture, Faculty of Agriculture, Universiti Putra Malaysia, Serdang, Malaysia

OPEN ACCESS

Edited by:
Victoria J. Brookes,
The University of Sydney, Australia

Reviewed by:
Georgina Limon,
Pirbright Institute, United Kingdom
Bouda Vosough Ahmadi,
European Commission for the Control of Foot and Mouth Disease (EuFMD), Italy

****Correspondence:***
Norhariani Mohd Nor
norhariani@upm.edu.my

Specialty section:
This article was submitted to Veterinary Epidemiology and Economics, a section of the journal Frontiers in Veterinary Science

Received: *19 December 2020*
Accepted: *31 August 2021*
Published: *08 October 2021*

Citation:
Mohd Yazid SH, Mohd Daud H, Azmai MNA, Mohamad N and Mohd Nor N (2021) Estimating the Economic Loss Due to Vibriosis in Net-Cage Cultured Asian Seabass (Lates calcarifer): Evidence From the East Coast of Peninsular Malaysia. Front. Vet. Sci. 8:644009. doi: 10.3389/fvets.2021.644009

This study aims to estimate the economic loss due to vibriosis in the production of Asian seabass in floating net-cages on the east coast of Peninsular Malaysia. Asian seabass has contributed significantly to Malaysia's economic activities and food security. However, its production can be hindered by the occurrence of diseases, such as vibriosis, causing severe economic losses to farmers. A questionnaire-based survey was conducted on 14 small-scale monoculture Asian seabass net-cage farms. Using a stochastic bioeconomic model and inputs from the survey, existing literature, and expert opinion, the economic losses were determined. Moreover, this model considered the prevalence of *Vibrio* spp. at a farm on the east coast and the risk posed by its infection from hatcheries. The results showed that 71.09% of Asian seabass simulated in the stochastic model survived. The mortality rate due to vibriosis and other causes was at 16.23 and 12.68%, respectively. The risk posed by *Vibrio* spp. infection from hatcheries contributed to 2.77% of the increase in Asian seabass mortality. The stochastic model estimated that the total cost of producing a tail of Asian seabass was €2.69 per kilogram. The economic loss of vibriosis was estimated at €0.19 per tail per kilogram, which represents 7.06% of the total production cost of Asian seabass per kilogram. An increase in the prevalence of clinical vibriosis and vibriosis case fatality rate at 42 and 100%, respectively, will lead to an increase in the cost of grow-out Asian seabass by €0.29 per tail from the default value. An increase in pellet price per kilogram by €1.38 and feed conversion ratio pellet by 0.96 will consequently increase the cost of grow-out Asian seabass by €2.29 per tail and €0.82 per tail, respectively. We find that the occurrence of *Vibrio* spp. infection at the hatchery level can contribute to an increased risk in the mortality of Asian seabass during the grow-out phase. Hence, we also need to focus on the control and prevention of vibriosis infection from hatcheries.

Keywords: Asian seabass, net-cage culture, vibriosis, economic loss, stochastic model

INTRODUCTION

Asian seabass (*Lates calcarifer*, Bloch 1790) is a euryhaline fish species that tolerates culture crowding and a wide physiological tolerance (1). Asian seabass culture was initiated in Thailand during the early 1970s and expanded to its neighboring countries, such as Indonesia, the Philippines, Singapore, Taiwan, Vietnam, and Malaysia, between the 1980s and 1990s (1). In Malaysia, Asian seabass is commonly cultured in floating net-cages, ponds, tanks, and enclosures (2–4). Its grow-out phase in floating net-cages varies, depending on the final market size and location of grow-out. The grow-out phase for a fingerling size of 6.35 cm during stocking varies between 6 months for 0.7 kg of fish during harvest and 30 months for 3.5 kg of fish suitable for fileting (5, 6). As a carnivorous species, Asian seabass requires a diet with high protein content for its efficient growth. In Malaysia, Asian seabass is fed on commercially formulated feed and trash fish. While the average feed conversion ratios (FCRs) for Asian seabass is ∼4 and above for trash fish, they range between 1.5 and 2.1 for commercially formulated feed (7).

Animal diseases can affect the aquaculture production function by destroying basic resources, reducing the physical output or unit value of a production process, lowering the efficiency of a production process, and directly affect human well-being (8, 9); this can ultimately lead to economic losses in the aquaculture sector. Several viral, fungal, parasitic, and bacterial diseases have been reported to affect cage-cultured Asian seabass, which can further cause co-infections (10, 11). In Malaysia, brackish water aquaculture includes the production of Asian seabass, which accounted for 290,900 metric tons in 2018; however, it was a 10.3% decrease from its previous year's production (12). One of the primary factors leading to the fall in production has been attributed to the occurrence of infectious diseases (13). In this context, we focus on vibriosis, a common bacterial disease found in cage-cultured Asian seabass (11, 14). Some members of the genus *Vibrio* spp., such as *V. harveyi, V. alginolyticus*, and *V. vulnificus*, are associated with infections in fish, where the host exhibits clinical signs, such as skin ulceration, scale drops on the abdomen, and necrosis of the caudal fin (9, 14).

However, there exists little information regarding the economic losses caused by vibriosis in the Asian seabass cultured in floating net-cages. In the case of Asian shrimp culture, vibriosis has been reported to have caused losses of USD 1 billion (15). In 1978, loss due to vibriosis in cultured yellowtail (*Seriola quinqueradiata*) was estimated at USD 4.4 million in Japan (16). In the Chinese aquaculture industry, the *Vibrio* spp. infection contributed to a loss of USD 120 million in the early 1990s, where *V. fluvialis* was one of the main pathogens (17). In the early 1990s, outbreaks of *V. harveyi* in the shrimp hatcheries of Indonesia caused economic losses of more than USD 100 million (18). Furthermore, vibriosis was reported to have affected cultured marine fish in Malaysia, causing a loss of USD 7.4 million during the same period (19, 20). Recently, the costs of endemic vibriosis, including treatment and diagnosis costs, for an Asian seabass floating net-cage on the west coast of Peninsular Malaysia was estimated at USD 0.24 per tail (6); however, existing literature has not yet determined the economic loss resulting from vibriosis on the east coast of the country, which is an important area for marine aquaculture. Moreover, small subsistence cage-cultured farms usually do not adopt preventive measures for fingerlings brought from hatchery. Analyzing the risks posed by *Vibrio* spp. from the hatchery may improve our understanding of the influence of vibriosis during the grow-out phase. Consequently, it may improve farmers' awareness of the impact of diseases on production costs and thereby making better decision to reduce the economic losses.

This study aims to fill this research gap by examining the economic loss resulting from vibriosis in the production of Asian seabass in floating net-cages on the east coast of Peninsular Malaysia with the help of a stochastic bioeconomic model (6). Modeling is a useful tool in epidemiology for investigating diseases when experiments and field observations are impracticable (21). Since the bioeconomic model used in this study is stochastic, it enables us to introduce uncertainty in disease prevalence, estimate the losses due to diseases, and observe the consequences of various control strategies, such as fish vaccination, that can be adopted in the future. Similar models have been used in previous studies related to aquaculture and dairy young stock (22).

MATERIALS AND METHODS

The Model

Following a prior study (6), we employed a stochastic bioeconomic model built in Microsoft Excel® (Microsoft Corp., Redmond, WA, USA) using @Risk add-on (Palisade Corp., Ithaca, NY, USA) to estimate the economic losses due to vibriosis on the east coast of Peninsular Malaysia. Disease prevalence on the east coast could differ from that on the west coast because of the differences in their environmental characteristics, including the physicochemical parameters of water (10, 11). **Figure 1** presents the framework for the estimation of the economic loss due to vibriosis in Asian seabass in floating net-cages on the east coast of Peninsular Malaysia (23, 24). The economic and biological inputs obtained in this study were based on a survey conducted on the east coast (section Model inputs), existing literature, and expert opinion.

Our stochastic bioeconomic model comprised a total of 18 two-weekly stages that helped in determining the health status of Asian seabass. Moreover, it considered the risk posed by *Vibrio* spp. infection in hatcheries, as a result of farmers' inability to adopt preventive measures when cultivating fingerlings to grow-out cage culture. This model estimated the cost of grow-out from a body weight of 21 g to 1 kg within 210 days. **Supplementary Figure 1** in the Supplementary materials section presents the stochastic model that simulated the costs of the infected during the grow-out phase, and dead Asian seabass due to vibriosis. Our model assumed small-scale farm management on the east coast, where farm owners did not provide treatment to the infected or send diseased fish samples in the laboratory for diagnosis; therefore, there was no estimation of diagnosis and treatment cost for infected Asian seabass. The economic loss of vibriosis was estimated by the sum of variable costs to grow-out fish that died due to vibriosis divided

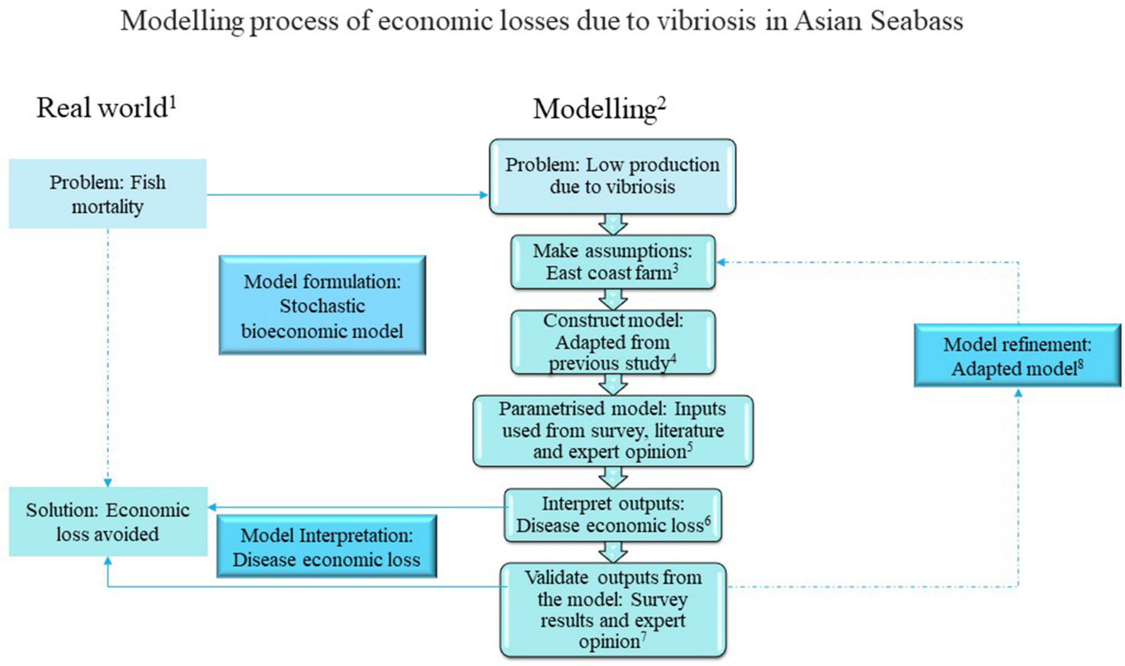


FIGURE 1 | A framework for the estimation of economic losses due to vibriosis in Asian seabass in floating net-cages on the east coast of Peninsular Malaysia. [1]In the real world, fish mortality is one of the major problems experienced by fish farms, which causes economic losses. A stochastic bioeconomic model is formulated to simulate this issue. [2]Bioeconomic modeling is used to simulate the problem of low production due to vibriosis: first, we state the relevant assumptions; second, we construct the model in Microsoft Excel using @Risk add-on; third, we select the suitable parameters of the model using biological and economic inputs from existing literature, survey results, and expert opinion; fourth, we interpret and validate the outputs to modify the model where necessary. [3]Following our assumptions, the bioeconomic model considers small-scale farm management on the east coast of Peninsular Malaysia; we conduct a survey that may help in model formulation. [4]We adapt the bioeconomic model from that of a previous study based on Asian seabass grow-out in cage farms on the west coast of Peninsular Malaysia. Details of the modeling of economic losses are shown in **Figure 2** and **Supplementary Figure 1**. [5]We obtain biological and economic inputs by conducting farm surveys, analyzing the prevalence of vibriosis from fish sampling, existing literature, and expert opinion (see **Tables 1–5**). [6]We interpret the model output in terms of economic losses from vibriosis (see section Analysis of the economic loss due to vibriosis using a stochastic model). [7]Survey results (see section Survey results) and expert opinion are used to validate the model output. [8]We modify the model by adapting small-scale farm management on the east coast of Peninsular Malaysia. This model includes the risk of *Vibrio* spp. infection from hatcheries and grow-out cage culture, assuming that the diagnosis or treatment for infected Asian seabass are not viable (assumption in the model refers to the inputs used in **Tables 1–5**).

by the number of Asian seabass that survived until market age (refer to **Supplementary Equation 1** in the Supplementary materials section). The model was simulated by 10,000 iterations, considering the currency exchange as €1= RM 4.94, on February 25, 2021.

A transition matrix was used to determine the health status of Asian seabass at each stage, referred to as a state, as shown in **Figure 2**. The model considered five states to determine the health status of Asian seabass: healthy, subclinical vibriosis, clinical vibriosis, dead due to vibriosis, and dead due to other causes. This study included only those cases where the fish was positive with at least one type of *Vibrio* sp. and did not display any clinical signs, which is defined as subclinical vibriosis. For clinical vibriosis, the fish must be positive with at least one type of *Vibrio* sp. and show either external or internal clinical signs or both. Inputs from the prevalence of subclinical *Vibrio* spp. infection, the prevalence of clinical *Vibrio* spp. infection, case fatality rate due to *Vibrio* spp., and mortality rate due to other reasons were used to determine the states.

Model Inputs

The inputs used in this study are based on the output of farm surveys, existing literature, and opinions from Malaysian fish disease experts. The biological input of the stochastic bioeconomic model includes the prevalence of subclinical and clinical *Vibrio* spp. in the east coast region, specifically Marang, Terengganu (unpublished data) (**Table 1**), the prevalence of subclinical and clinical *Vibrio* spp. in hatcheries (25), the prevalence of clinical *Vibrio* spp. (grow-out) from a fish farm in Pulau Ketam, Malaysia (**Table 1**) (11), case fatality rate during the grow-out phase with an average of 40% (26), number of deaths in Asian seabass due to other reasons (**Table 2**) (27), gain in body weight (28), seawater temperature (**Table 3**) (29), FCR for pellet (1.73–2.96) and trash fish feed (3.53–4.16) (7, 30–32), and feed attribution to gain in body weight (60% pellet; 40% trash fish) (32). Based on previous recommendations, we ensure that the amount of feed consumed per kilogram body weight was not more than 10% of the body weight (33). A summary of the biological inputs used in this study is shown in **Table 4**. The economic input of the stochastic bioeconomic model includes

Stage = n+1

Stage = n: State	Healthy (1)	Subclinical vibriosis (2)	Clinical vibriosis (3)	Dead due to vibriosis (4)	Dead due to other reasons (5)
Healthy (A)	1-sum (A2 and A5)	Prevalence of subclinical vibriosis (A2)[1]			Mortality rate (A5)
Subclinical vibriosis (B)	1-(B3)		Prevalence of clinical vibriosis (B3)[1]		
Clinical vibriosis (C)	1-(C4)			Case fatality rate (C4)	
Dead due to vibriosis (D)				1	
Dead due to other reasons (E)					1

FIGURE 2 | This transition matrix was adapted from a previous study (6). The state of fish at stage ($n + 1$) is dependent on its state at the previous stage (n). From the figure above, we can see that at stage n, a fish in a healthy state (cell A) can be subclinically infected with vibriosis (cell 2) at stage ($n + 1$), determined by the prevalence of subclinical vibriosis (A2). Within the following 2 weeks of subclinical infection with vibriosis (cell B), we assume that there will be a response from the fish's immune system, such that it will either become healthy (cell 1) or clinically infected with vibriosis (cell 3), determined by the prevalence of clinical vibriosis (B3). Within 2 weeks after acquiring a clinical infection with vibriosis (cell C), a fish can either become healthy (cell 1) or die (cell 4), which is determined by the case fatality rate (C4). If the state of the fish implies that it was dead in the previous stage (n), it will remain the same in the following stages (D4 and D5). [1]Indicates differences in the rate of infection, depending on the month of grow-out (11).

fingerling price (€0.24 per tail), pellet price (€1.26 per kilogram), trash fish price (€0.18 per kilogram), labor cost (€313 per month), maintenance cost (€10 per month), petrol cost (€17.59 per month), and utility cost (€4.99 per month) based on the output of the surveys conducted (**Table 5**).

Farm Survey

Malaysia is divided into Peninsular Malaysia and Borneo Island. Peninsular Malaysia is divided into the east coast and west coast. The east coast of Peninsular Malaysia consists of three states: Kelantan, Terengganu, and Pahang. A list of 209 floating net-cage farms in the three states was obtained from the Department of Fisheries (DOF), Ministry of Agriculture and Agro-food Industry, Malaysia. Using convenience sampling, we selected 39 farms to be surveyed between February and May 2017. During the survey, a face-to-face interview was conducted with the farm owner or representative of the workers at the farm with the help of a questionnaire. The questionnaire used in this study contains 122 questions, consisting of five sections that include questions on farmers' backgrounds, farm management and background, general fish health information, and knowledge of vibriosis with reference to previous studies (6). The data collected were based on the latest fish culture cycle of 2016.

Model Validation

The survey results were used to validate the model output for feed. Furthermore, the opinions of Malaysian fish disease experts were used to validate the model output for the mortality rate due to vibriosis.

Sensitivity Analysis

Sensitivity analyses were conducted on crucial economic and biological inputs to determine the impact of a change in input on the costs of grow-out in Asian seabass per kilogram per tail. The default input value was changed one at a time to a lower or higher value. The following economic inputs were changed: (i) fingerling price per tail with default a value at €0.24 was changed one at a time to €0.20 (– €0.04 from default value) and further changed to €0.32 (+ €0.06 from default value); (ii) trash fish price per kilogram with a default value at €0.18 (– €0.07; + €0.53); (iii) pellet price per kilogram with a default value at €1.26 (– €0.46; + €1.38); (iv) labor cost per month with a default value at €313 (– €70; + €70). The following biological inputs were changed: (i) FCR pellet with a default value most likely at 2 (−0.27; +0.96) (7, 31, 32); (ii) FCR trash fish with a default value most likely at 4 (−0.47; +0.16) (7, 30, 32); (iii) prevalence of subclinical *Vibrio* spp. during grow-out phase (0%, 60%) (unpublished data); (iv) prevalence of clinical *Vibrio* spp. during grow-out phase (11%, 40%) (11); (v) *Vibrio* spp. case fatality during grow-out phase with a default value most likely at 40% (−40%, +60%) (26) (**Table 6**).

Data Management and Analysis

Data collected from the survey were inserted and edited using Microsoft Excel® (Microsoft Corp. Inc, Ithaca). We conducted a descriptive analysis using R-version 3.3.1 (R Foundation

TABLE 1 | Data on the prevalence of subclinical and clinical *Vibrio* spp.

Month	Prevalence of subclinical *Vibrio* spp.[a,b]	Prevalence of clinical *Vibrio* spp.[c]
January	0.20	0.17
February	0.32	0.12
March	0	0.12
April	0.60	0.11
May	0.32	0.14
June	0.32	0.24
July	0.60	0.32
August	0.40	0.40[b]
September	0.32	0.28
October	0.25	0.24
November	0.20	0.16
December	0.32	0.42

Subclinical Vibrio spp. is defined as Asian seabass positive with at least one species of Vibrio that do not exhibit clinical signs. Clinical Vibrio spp. is defined as Asian seabass positive with at least one species of Vibrio, exhibiting either internal or external clinical signs or both.

[a] *Constructed following a stochastic bioeconomic model, using Riskpert [minimum, most likely, and maximum prevalence, RiskTruncate (0,1)] due to insufficient data. For example, for January, we have Riskpert [0, 0.20, 0.60, RiskTruncate (0,1)].*

[b] *Prevalence of Vibrio spp. at Sungai Marang, Terengganu (unpublished data). Sampling is conducted between October 2018 and August 2019. Vibrio spp. isolated from Asian seabass in this study are V. fluvialis, V. vulnificus, V. alginolyticus, and V. parahaemolyticus.*

[c] *Prevalence of clinical Vibrio spp. at Pulau Ketam, Selangor (11).*

for Statistical Computing; Vienna, Austria). Additionally, we conducted a descriptive analysis on the output of the stochastic model using the StatTools add-on (Palisade Corp. Ithaca, NY, USA) in Microsoft Excel® (Microsoft Corp. Redmond, WA, USA).

RESULTS

Analysis of the Economic Loss Due to Vibriosis Using a Stochastic Model

Based on our stochastic model, 71.09% of the simulated Asian seabass survived for 210 days post-stocking with an average body weight of 1,060 g (5–95% percentiles: 1,045–1,075 g). A total of 1,494 g of commercially formulated feed and 1,317 g of trash fish were consumed per tail. The mortality rate due to vibriosis and other causes was 16.23 and 12.68%, respectively. The total average cost of producing a tail of Asian seabass was €2.69, consisting of €2.36 variable costs, €0.02 fixed costs, and €0.31 provision costs due to mortality (**Supplementary Equation 21** in the Supplementary materials section). The total economic loss due to vibriosis was estimated at €0.19 per tail (**Table 7**), representing 7.06% of the total production cost of Asian seabass per kilogram (**Supplementary Equation 22** in the Supplementary materials section).

Sensitivity analysis conducted on biological inputs showed that the costs of grow-out in Asian seabass per tail were most sensitive to changes in the FCR for pellet and case fatality rate due to vibriosis. When the FCR for pellet increased by 0.96 from its default value, the costs of grow-out in Asian seabass increased by €0.82 per tail. When the FCR for pellet decreased by 0.27 from its default value, the costs of grow-out decreased by €0.37 per tail. Since the case fatality rate due to vibriosis increased to 60% from its default value (40%), the costs of grow-out increased by €0.29 per tail. When the case fatality rate due to vibriosis was reduced to 0%, the costs of grow-out decreased by €0.12 per tail. When the prevalence of clinical vibriosis was at 42%, the costs of grow-out increased by €0.29 per tail. When the prevalence of clinical vibriosis was at 11%, the costs of grow-out decreased by €0.08

TABLE 2 | The number of dead fish per stage is modeled using Riskpert (minimum, most likely, and the maximum number of dead).

Grow-out stage	Post-stocking (days)	Minimum number of dead	Most likely number of dead	Maximum number of dead
1	1	210	350	1,092
2	14	210	350	1,092
3	28	210	350	1,092
4	42	70	140	280
5	56	42	112	210
6	70	28	70	126
7	84	0	56	182
8	98	0	56	182
9	112	14[a]	56	182
10	126	14	70	182
11	140	14	70	182
12	154	14	70	182
13	168	14	70	182
14	182	14	70	182
15	196	14	70	182
16	210	14	70	182

For example, we observe Riskpert (0, 300, 1,500) due to uncertainty in mortality based on previous data (27).

[a] *The minimum number of dead increases after 112 days post-stocking, as the weight of Asian Sea bass has reached 400 g that is the market weight under grading.*

TABLE 3 | Seawater temperature on the east coast of Peninsular Malaysia (29).

Month	Average temperature (°C)	Standard deviation
January	27.05	0.25
February	27.47	0.23
March	28.12	0.17
April	29.25	0.12
May	29.93	0.22
June	29.90	0.17
July	29.70	0.17
August	29.25	0.12
September	29.23	0.05
October	29.55	0.05
November	29.15	0.05
December	28.10	0.13

The data are used in the stochastic bioeconomic model to estimate the gain in body weight (28) by using a normal distribution [RiskNormal (average, standard deviation)]. For example, for January, we have RiskNormal (27.05, 0.25).

TABLE 4 | Other biological inputs used in the stochastic bioeconomic model for grow-out in Asian seabass.

Variable	Data	Sources
Percentage of gain in body weight attributed to feed		
Before 2 months of age	100% by pellet	[Farm survey, (32)]
Between 2 and 4 months of age	80% by pellet; 20% by trash fish	[Farm survey, (32)]
After 4 months of age	60% by pellet: 40% by trash fish	(32)
The feeding rate per day		
Before fingerlings attain a body weight of 100 g	3	[Farm survey, (30, 33)]
After fingerlings attain a body weight of 100 g	2	Farm survey
The feed conversion ratio for trash fish (average)[a]	1: 4	(7, 30, 32)
Minimum–maximum	3.53–4.16	
The feed conversion ratio for pellet (average)[a]	1:2	(7, 31, 32)
Minimum–maximum	1.73–2.96	
Vibriosis		
Prevalence of subclinical *Vibrio* spp. in hatcheries[a]	0.077	(25)
Prevalence of clinical *Vibrio* spp. in hatcheries[a]	0.083	(25)
Case fatality rate (minimum–maximum)[a]	40% (0%−100%)	(25)
Body weight gain constants		
K	2.2495	(28)
X	−0.327	
Y	0.015	
Z	−0.000203	
a	−0.01	
b	0.72	
Body weight loss (*Vibrio* spp.)	0.69% from body weight	(11)
Time taken to do activities		
Cleaning net (seconds per tail)	2.7	Aquatic veterinarian
Feeding (seconds per tail)	0.8	Aquatic veterinarian
Grading (seconds per tail)	1.8	Aquatic veterinarian

[a]*Modeled using Riskpert (minimum, most likely, and maximum number). An example of the case fatality rate is Riskpert (0, 0.40, 1).*

TABLE 5 | Economic inputs used in the stochastic model.

Variables	Price (€)	Source
Fingerling at 3 to 4 inches (per tail)	0.24	Farm survey
Market fish (per kilogram)	3.29	Farm survey
Pellet (per kilogram)	1.26	Farm survey
Trash fish (per kilogram)	0.18	Farm survey
Labor wage (per month)	313	Farm survey
Maintenance (per month)	10	Farm survey
Petrol (per month)	17.59	Farm survey
Utility (per month)	4.99	Farm survey

per tail. When the prevalence of subclinical vibriosis increased to 60%, the costs of grow-out increased by €0.12 per tail. When the prevalence of subclinical vibriosis was reduced to 0%, the costs of grow-out decreased by €0.09 per tail. When the FCR for trash fish increased by 0.16, the costs of grow-out Asian seabass increased by €0.02 per tail. When FCR for trash fish decreased by 0.47, the costs of grow-out decreased by €0.03 per tail (**Figure 3**).

Based on the sensitivity analysis conducted on economic inputs, when the price of pellet per kilogram increased by €1.38 from its default price of €1.26, the costs of grow-out increased by €2.29 per tail. When the price of pellet per kilogram decreased by €0.46 from its default price, the costs of grow-out decreased by €0.75 per tail. Similarly, an increase in the price of trash fish per kilogram by €0.53 increased the costs of grow-out by €0.75 per tail. When the price of trash fish per kilogram decreased by €0.07, the costs of grow-out decreased by €0.10 per tail. An increase in the fingerling price per tail by €0.06 increased the costs of grow-out by €0.09 per tail. A decrease in the fingerling price per tail by €0.04 decreased the costs of grow-out by €0.06 per tail. An increase in the wage of labor per month by €70 increased the costs of grow-out by €0.01 per tail and vice versa (**Figure 4**).

Survey Results

The average age of the farmers was 54 years (minimum–maximum: 37–70 years). All the observed farmers ($n = 14$) were male with the highest level of educational attainment being secondary education ($n = 8$). We observed that the farmers ($n = 14$) did not know about the vibriosis disease, including its clinical signs. However, majority of the farmers attributed the reasons for sick and dead fish to both infectious and non-infectious agents ($n = 10$), and non-infectious agents only ($n = 4$). The median morbidity rate at the farms was perceived as 50% per cycle (minimum–maximum: 17.5%−80%), while the median mortality rate was perceived as 50% per cycle (minimum–maximum: 17.5%−80%). Although 50% of the farmers ($n = 7$) provided treatment using freshwater, the remaining did not resort to any

TABLE 6 | Sensitivity analyses for biological and economic inputs.

Variables	Default value (€)	Change in value (lowest change; highest change) (€)	Source
Fingerling	0.24	−0.04; +0.06	Farm survey
Trash fish (per kilogram)	0.18	−0.07; +0.53	Farm survey
Pellet price (per kilogram)	1.26	−0.46; +1.38	Farm survey
Labor wage (per month)	313	−70; +70	Farm survey
Feed conversion ratio (pellet)	2	−0.27; +0.96	(7, 31, 32)
Feed conversion ratio (trash fish)	4	−0.47; +0.16	(7, 30, 32)
Prevalence of subclinical vibriosis	Refer to **Table 1**	(−0 to −0.60); (+0 to +0.60)	Unpublished data
Prevalence of clinical vibriosis	Refer to **Table 1**	(−0 to −0.31); (+0; to +0.31)	(11)
Vibriosis case fatality rate	0.40	−0.40; +0.60	(26)

TABLE 7 | The cost of grow-out for Asian seabass in cage culture per tail from 20 to 1,060 g (5–95% percentiles: 1,045–1,075 g) within 210 days of using the stochastic model.

Variables	Average cost (5%−95% percentiles) (€)	Type of costs	Average cost (5%−95% percentiles) (€)
Fingerling	0.24	Variable[a]	0.24
Feed			2.11 (1.87–2.41)
Trash fish	0.23 (0.22–0.24)		
Pellet	1.87 (1.64–2.18)		
Labor	0.012 (0.012–0.012)		0.012 (0.012–0.012)
Total			2.36 (2.12–2.66)
Maintenance	0.008 (0.008–0.008)	Fixed[a]	
Petrol	0.012 (0.012–0.012)		
Utility	0.004 (0.004–0.004)		
Total			0.02 (0.02–0.02)
Losses (total mortality)		Provision[a]	0.31
Due to vibriosis	0.19		
Due to other cause	0.12		
Variables	Average cost (5%−95% percentiles) (€)	Type of profit[a]	Profit
Fish (g)	1,060 [1,045–1,075]	Revenue	3.49 (3.44–3.54)
		Gross margin	1.12 (0.83–1.37)
		Net profit	1.10 (0.72–1.26)

[a] *Refer to* ***Supplementary Equations 11–20*** *in the Supplementary materials.*

type of treatment ($n = 7$). Majority of the farmers (85%, $n = 6$) reported that none of the fish recovered after treatment.

The median of Asian seabass net-cage per farm ($n = 14$) was 13 cages (minimum–maximum: 6–32 cages) with a median cage size of 9.30 m^2 (minimum–maximum: 7.44–18.57 m^2). The median stocking density per square meter of a net-cage was 67 tails (minimum–maximum: 18–107 tails). The median stocking density per farm ($n = 14$) was 3,000 tails (minimum–maximum: 1,000–12,000 tails) with a stocking fingerling size of 10.16 cm (minimum–maximum: 6.35–27.94 cm) ($n = 14$). The median grading frequency at the farms was three times per cycle (minimum–maximum: 1–4 times per cycle). The median grow-out period per cycle ($n = 14$) was 12 months (minimum–maximum: 6–24 months) with the median size of fish being 1 kg (minimum–maximum: 0.7–1.5 kg). The median number of Asian seabass harvested per cycle ($n = 14$) was 1,350 tails (minimum–maximum: 400–4,800 tails). The median tonnage of Asian seabass harvested per cycle ($n = 14$) was 1.05 metric tons (minimum–maximum: 0.34–4.8 metric tons). On average, the feeding frequency at the farms surveyed was twice per day in the first month of culture, which was consequently reduced to one and two times per day. None of the surveyed farms were accredited with the Malaysia Good Aquaculture Practices (MyGAP) certification.

On average, following the monthly operational costs incurred by the surveyed farms, the highest cost was attributed to commercially formulated feed (78.7%), followed by trash fish (16.33%), fuel (2.64%), and maintenance (1.56%). The least amount of expenditure was attributed to utility (0.77%) (**Table 8**). The estimated median cost of producing 1,350 tails per kilogram of Asian seabass was €3,288 per cycle. The median cost of fingerlings ($n = 14$) was €728 per cycle. The median cost of feed

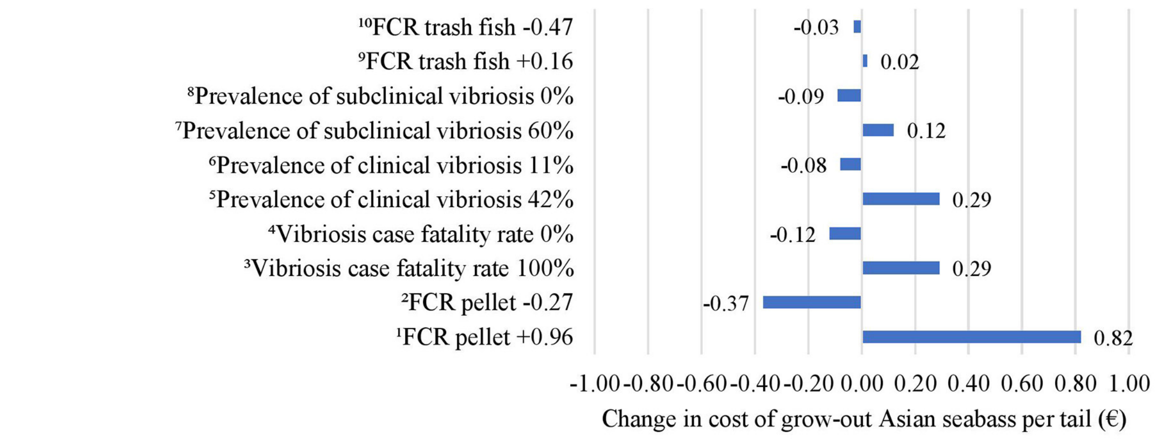


FIGURE 3 | Impact of change in biological inputs on the costs of grow-out in Asian seabass per tail. [1]When the FCR for pellet increases by 0.96 from its default value, the costs of grow-out increase by €0.82 per tail. [2]When the FCR for pellet decreases by 0.27 from its default value, the costs of grow-out decrease by €0.37 per tail. [3]When the case fatality rate due to vibriosis is 100%, the costs of grow-out increase by €0.29 per tail. [4]When the case fatality rate due to vibriosis is 0%, the costs of grow-out decrease by €0.12 per tail. [5]When the prevalence of clinical vibriosis is 42%, the costs of grow-out increase by €0.29 per tail. [6]When the prevalence of clinical vibriosis is 11%, the costs of grow-out decrease by €0.08 per tail. [7]When the prevalence of subclinical vibriosis is at 60%, the costs of grow-out increase by €0.12 per tail. [8]When the prevalence of subclinical vibriosis is at 0%, the costs of grow-out decrease by €0.09 per tail. [9]When FCR for trash fish increases by 0.16, the costs of grow-out Asian seabass increase by €0.02 per tail. [10]When FCR for trash fish decreases by 0.47, the costs of grow-out decrease by €0.03 per tail.

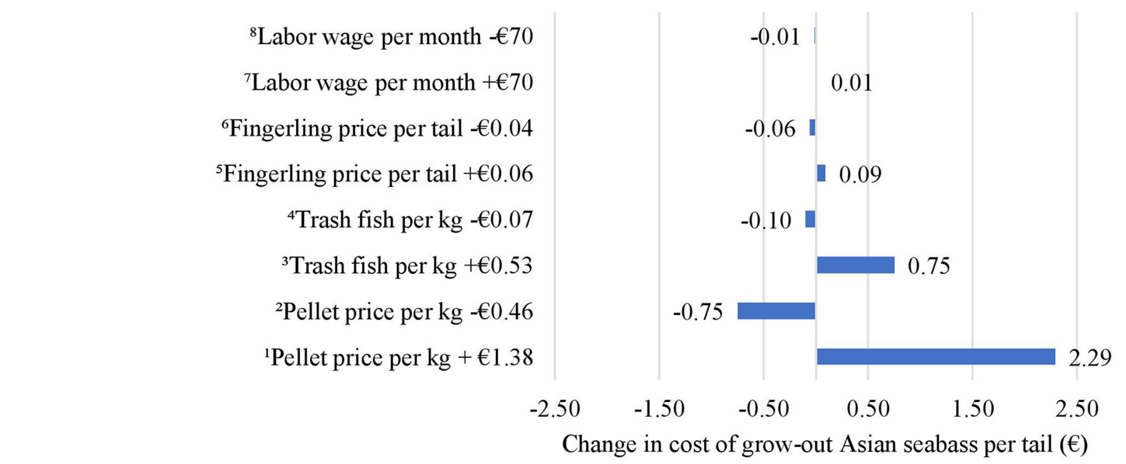


FIGURE 4 | Impact of changes in economic inputs on the costs of grow-out in Asian seabass per tail. [1]When the price of pellet per kilogram increases by €1.38 from its default price, the costs of grow-out increase by €2.29 per tail. [2]When the price of pellet per kilogram decreases by €0.46 from its default price, the costs of grow-out decrease by €0.75 per tail. [3]When the price of trash fish per kilogram increases by €0.53, the costs of grow-out increase by €0.75 per tail. [4]When the price of trash fish per kilogram decreases by €0.07 less, the costs of grow-out decrease by €0.10 per tail. [5]When the fingerling price per tail increases by €0.06, the costs of grow-out increase by €0.09 per tail. [6]When the fingerling price per tail decreases by €0.04, the costs of grow-out decrease by €0.06 per tail. [7]When the wage of labor per month increases by €70, the costs of grow-out increase by €0.01 per tail. [8]When the wage of labor per month decreases by €70, the costs of grow-out decrease by €0.01 per tail.

($n = 14$) was €2,281. The median expenditure for labor ($n = 14$), maintenance ($n = 9$), fuel ($n = 14$), and utility ($n = 14$) were €0 per cycle.

DISCUSSION

According to our model, the estimated economic loss due to vibriosis is €0.19 per tail, representing 7.06% of the total production cost of Asian seabass per kilogram. A previous study reported the cost of endemic vibriosis to be €0.004 higher than the results reported in our study since the study included diagnosis and treatment costs (6). Loss due to vibriosis in this study could be higher than the previous study if the diagnosis and treatment were included due to the risk of *Vibrio* spp. infection from hatcheries and higher prevalence of *Vibrio* spp. on the east coast. Studies on the costs and benefits of vibriosis control and prevention through vaccination in hatcheries and constructing a better grow-out net-cage farms on the east coast should be taken

TABLE 8 | Descriptive results of continuous data on operational costs per month.

Variable	Median (€)	Mean (€)	Minimum (€)	Maximum (€)	Number of farms (n = 14)
Monthly estimation[a]					
Commercially formulated feed	264	506	78	2,370	14
Trash fish	94	105	0	288	8
Petrol per diesel	0	17	0	200	13
Maintenance (e.g., net and cage repair)	0	10	0	90	9
Utility (electricity)	0	4.93	0	48	14

[a] *The median grow-out period per cycle at survey farms (n = 14) was 12 months (minimum–maximum: 6–24 months).*

into consideration. In this study, the surveyed farmers estimated their production as 1,350 tails of 1 kg of Asian seabass per cycle. For example, considering the analysis of the cage culture area and the costs of vibriosis using model in this study, there could be provisional costs estimated at €265 (8.06%) in addition to the total cost of €3,288 per cycle. Analysis in this study revealed that 16.23% of simulated Asian seabass died due to vibriosis, which is in contrast to earlier findings that reported a 6.89% mortality rate due to vibriosis from the stochastic model (6). This could be due to the differences in the occurrence of vibriosis in the observed farms. Floating net-cage farms located in the east coast area are prone to flooding because of the annual northeast monsoon that causes fluctuations in water physicochemical parameters. All the floating net-cage farms observed in this study were situated close to the land; in addition, the river is known for low water tidal current episodes that cause river water to become stagnant, inevitably providing favorable conditions for the growth of *Vibrio* spp. Following the sensitivity analysis, other than the feed that greatly influences the costs of grow-out in Asian seabass per tail, disease such as high rate of *Vibrio* spp. infection, particularly fatality rate due to vibriosis and prevalence of clinical vibriosis, highly influences the costs of grow-out in Asian seabass. An increase in vibriosis case fatality rate and the prevalence of clinical vibriosis at a maximum rate of 100 and 42%, respectively, would increase the costs of grow-out by €0.29 more per tail from its default value, thereby increasing the costs by 12%. If measures of controlling the occurrences of diseases at farms are not taken, it can cause significant losses, resulting in a high cost of grow-out in Asian seabass per tail. An increase in the production costs due to disease could be overcome by adopting suitable biosecurity measures at farms, such as minimal handling of fish (e.g., during fish stocking and grading), appropriate disposal of dead fish, quarantine of sick fish, use of appropriate feeds, and regularly conducting laboratory analyses to check the status of fish health. In addition, implementation of vaccination and chemoprophylaxis as preventive measures should be considered to mitigate economic losses (33, 34).

This study presented the results of a survey of 14 small-scale monoculture Asian seabass farms in the east coast of Malaysia based on the information provided by its Department of Fisheries. Despite the small sample size, the study conducted surveys on cage culture farms in the states of Kelantan and Terengganu, considering different farm sizes and management inputs, which can provide insights into small-holder cage culture farms. Our study showed that the market price of Asian seabass in the east coast was higher by €0.19 as compared to the west coast (6), which could be a result of a less fish supply in the east coast. Moreover, production in the east coast could be affected by the yearly harsh monsoon season and Asian seabass on the east coast is mostly marketed to the west coast. It should be noted that the total cost of grow-out for the tail of Asian seabass was estimated at €2.69 in this study, which is €0.28 lower than that on the west coast (6). In addition to the low cost of trash fish, we observed that all cage culture sites were close to land; thus, the farmers did not have to spend significantly on fuel and maintenance costs in comparison to the west coast region of Peninsular Malaysia (6). We found that the net profit obtained from the east coast farm was €0.44 per tail higher than that in the west coast (6).

In this study, we found that the risks posed by *Vibrio* infection from hatcheries contributed to 2.77% of the increase in Asian seabass mortality due to vibriosis. A previous study on marine fish fry, that is Asian seabass, red snapper, and hybrid grouper, reported the prevalence of *Vibrio* spp. in more than half (55%) of the fish sampled (25). It was stated that the major source of infection by pathogens could be transmitted through the feed at the hatchery (25, 35), and *Vibrio* spp. were introduced to the grow-out cages by an infected fry once they were transferred. The transfer of fingerlings must be carried out cautiously to overcome economic losses. It is recommended for the farmers to stock high-quality fingerlings obtained from reputable suppliers and are free from diseases. The transport used to deliver the fingerlings from hatcheries must be cleaned, rinsed, and disinfected before and after delivery to the farm. In addition, the fingerlings must be quarantined upon their arrival before being stocked into net-cages; this will allow the farmers to observe any prevailing disease infection and help the fish to adapt to its new environment by minimizing its stress associated with the new environment (33).

From the stochastic model, the total variable cost of grow-out per kilogram of Asian seabass was estimated at €2.36 per tail. The findings are consistent with the survey results, which showed that the estimated median cost of grow-out for 1,350 tails of Asian seabass per kilogram was €3,288 per cycle, implying that the cost of producing a tail of Asian seabass with a body weight of 1 kg is €2.43. Previous findings reported the total variable costs of grow-out for Asian seabass per kilogram using a stochastic model to be slightly higher at €2.59 per tail (6). The observed low variable cost estimated in this study could be due to the differences in the prices of feeds. Majority of farmers in the east coast depend on discarded fish heads instead of whole fish as feed since they are readily available with much lower cost. However, these findings need to be interpreted with caution due to the uncertainty associated with the FCR for fish heads, which could be higher than that for a whole fish and could affect the growth rates (7), and a longer grow-out period to reach the market size, consequently increasing the production costs of the farm. To the best of our knowledge, no prior study has reported on the FCR for fish heads; hence, it is suggested that future research needs to focus on this gap. Our study found that commercial pellets were the largest cost component at €1.87 per tail, which was 69% of the total costs of grow-out per tail in Asian seabass. These findings are consistent with previous studies (5–7). In fact, the cost of grow-out in Asian seabass was most sensitive to changes in pellet prices and the FCR for pellet. A decrease in the pellet price by €0.46 from its default value (36% of the price of pellet per kilogram) could reduce the costs of grow-out Asian seabass by €0.75 per tail (31% lower costs) while a lower FCR of pellet by 0.27 from its default value (14% lower FCR) could reduce the cost of grow-out in Asian seabass by €0.37 per tail (16% lower costs). To improve feed and feeding efficiency, future studies should focus on the development of feed quality with an appropriate formulation and stable protein content that is highly digestible by Asian seabass in its different stages of growth and development. Additionally, suitable feeding regimes, feeding protocols, effective feeding systems, and on-farm feed management strategies and technologies should be developed, which can be implemented by farmers.

In conclusion, the stochastic model employed in this study estimated the economic losses due to vibriosis in Asian seabass cage culture in the east coast of Peninsular Malaysia at €0.19 per tail, which represents 7.06% of the total production cost of Asian seabass per kilogram. The total cost of producing a tail of Asian seabass was estimated at €2.69 per kilogram per tail, which comprises variable costs, such as the sum of operational costs at €2.36, fixed costs at €0.02, and provision costs due to mortality at €0.31. The findings from this study provide insights into the economic losses due to vibriosis in the context of cage-cultured Asian seabass kept in the east coast of Peninsular Malaysia. The findings of this study can contribute toward decision-making in the context of the prevention and control of fish diseases. Additionally, this study provides a better understanding on the cost of production of Asian seabass in floating net-cages for farmers and increase their awareness of the impact of such disease on Asian seabass production. Furthermore, this can help the farmers in managing their farm by practicing good farm management, such as proper record-keeping, ensuring the optimal stocking density of fish per net-cage, proper feeding management, regular water quality monitoring, and implementing appropriate biosecurity measures, such as proper equipment sanitation, farm access control, quarantine and treatment of sick fish, and appropriate disposal of dead fish at the farm; consequently, this may improve the economy of the aquaculture industry. The risk associated with *Vibrio* spp. infection from hatcheries has contributed to the mortality of Asian seabass during the grow-out phase. Hence, attention needs to be paid toward the control and prevention in the transmission of *Vibrio* spp. from hatcheries.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

NMN, SHMY, and HMD: conceptualization. NMN and SHMY: methodology. NMN and HMD: validation. SHMY and NMN: formal analysis. SHMY, NMN, MA, NM, and HMD: data curation. SHMY: original draft preparation. NMN, HMD, and MA: writing, review, and editing. All authors have reviewed and read the manuscript.

FUNDING

This study was financially supported by the Ministry of Higher Education, Malaysia under the Transdisciplinary Research Grant Scheme (Project id mygrants: 14872; Reference code: TRGS/1/2019/UPM/02/5/; Vot UPM: 5535902) (Title: Evaluating the effects of vibriosis vaccination on socio-economic of cage culture marine fish industry). SHMY is the recipient for Special Graduate Research Allowance (SGRA) scheme at Universiti Putra Malaysia.

ACKNOWLEDGMENTS

We would like to thank fish farmers for their participation in our survey and Prof. Dr. Mohd Zamri Saad for his valuable contributions as a marine sea-cage culture expert, which helped to improve this manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.644009/full#supplementary-material

REFERENCES

1. Food and Agriculture Organization of the United Nations (FAO). *Cultured Aquatic Species Information Programme (Lates calcarifer)* (2009). Available online at: http://www.fao.org/fishery/culturedspecies/Latescalcarifer/en (accessed October 30, 2020).
2. Food and Agriculture Organization of the United Nations (FAO). *National Aquaculture Sector Overview*. (2020). Available online at: http://www.fao.org/fishery/countrysector/nasomalaysia /en (accessed October 31, 2020).
3. Islam GMN, Tai SY, Kusairi MN. A stochastic frontier analysis of technical efficiency of fish cage culture in Peninsular Malaysia. *Springerplus*. (2016) 5:1127. doi: 10.1186/s40064-016-2775-3

4. Lembaga Kemajuan Ikan Malaysia (LKIM). *Malaysian Fisheries Development Authority: Aquaculture Development*. (2015). Available online at: https://www.lkim.gov.my/en/aquaculture-development/ (accessed October 28, 2020).
5. Mohd Yazid SH, Mohd Nor N, Mohd Daud H. Socio-economics of floating net-cage marine fish farms in Peninsular Malaysia. *Fishmail*. (2019) 27:5–9.
6. Mohd Nor N, Mohd Yazid SH, Mohd Daud H, Azmai MNA, Mohamad N. Costs of management practices of Asian seabass (*Lates calcarifer* Bloch, 1790) cage culture in Malaysia using stochastic model that includes uncertainty in mortality. *Aquaculture*. (2019) 510:347–52. doi: 10.1016/j.aquaculture.2019.04.042
7. Petersen EH, Phuong TH, Dat NK, Tuan VA, Truc LV. *Bioeconomics of Asian seabass, Lates calcarifer, culture in Vietnam. ACE Discussion Paper 2011/3*. (2011). Available online at: www.advancedchoiceeconomics.com.au (accessed January 25, 2021).
8. Mclnerney J. Old economics for new problems-livestock disease: presidential address. *J Agric Econ*. (1996) 47:295–314. doi: 10.1111/j.1477-9552.1996.tb00695.x
9. Mohamad N, Amal MNA, Md Yasin IS, Saad MZ, Nasruddin NS, Al-Saari N, et al. Vibriosis in cultured marine fishes: a review. *Aquaculture*. (2019) 512. doi: 10.1016/j.aquaculture.2019.734289
10. Abdullah A, Ramli R, Ridzuan MSM, Murni M, Hashim S, Sudirwan F, et al. The presence of *Vibrionaceae*, *Betanodavirus* and *Iridovirus* in marine cage-cultured fish: role of fish size, water physicochemical parameters and relationships among the pathogens. *Aquac Rep*. (2017) 7:57–65. doi: 10.1016/j.aqrep.2017.06.001
11. Mohamad N, Mustafa M, Amal MNA, Saad MZ, Md Yasin IS, Al-saari N. Environmental factors associated with the presence of *Vibrionaceae* in tropical cage-cultured marine fishes. *J Aquat Anim Health*. (2019) 31:154–67 doi: 10.1002/aah.10062
12. Department of Statistic Malaysia (DOSM). *Selected Agricultural Indicators, Malaysia, 2019*. (2019). Available online at: https://www.dosm.gov.my/v1/index.php?r=column/cthemeByCat&cat=72&bul_id=SEUxMEE3VFdBcDJhdUhPZVUxa2pKdz09&menu_id=Z0VTZGU1UHBUT1VJMFlpaXRRR0xpdz09 (accessed October 29, 2020).
13. Department of Fisheries Malaysia (DOFM). *Malaysian Fishing Industry Scenario*. (2017). Available online at: https://www.dof.gov.my/index.php/pages/view/42 (accessed November 1, 2020).
14. Ina-Salwany MY, Al-Saari N, Mohamad A, Fathin-Amirah M, Mohd A, Amal MNA, et al. Vibriosis in fish: a review on disease development and prevention. *J Aquat Anim Health*. (2018) 31:3–22. doi: 10.1002/aah.10045
15. GAA. Cause of EMS shrimp disease identified. In: *GAA News Release*. (2013). Available online at: http://www.gaalliance.org/newsroom (accessed October 16, 2020).
16. Sindermann CJ. Disease in marine aquaculture. *Helgoländer Meeresuntersuchungen*. (1984) 37:505–30. doi: 10.1007/BF01989327
17. Wei Q. Social and economic impacts of aquatic animal health problems in aquaculture in China. In: *FAO Fisheries Technical Paper* (2002). Available online at: http://www.fao.org/3/y3610e/y3610E06.htm (accessed April 14, 2021).
18. Rukyani A. Indonesia. In: *Thematic Review on Management Strategies for Major Diseases in Shrimp Aquaculture. A Component of the WB/NACA/WWF/FAO Program on Shrimp Farming and the Environment in Cebu* (2000). p. 59–64. Available online at: http://www.enaca.org/shrimp (accessed April 28, 2021).
19. Wei LS, Wee W. Diseases in aquaculture. *Res J Ani Vet Sci*. (2014) 7:1–6.
20. Bondad-Reantaso MG, Subasinghe RP, Arthur JR, Ogawa K, Chinabut S, Adlard R, et al. Disease and health management in Asian aquaculture. *Vet Parasitol*. (2005) 132:249–72. doi: 10.1016/j.vetpar.2005.07.005
21. Thursfield M. *Veterinary Epidemiology*. 3rd ed. UK, Oxford: Blackwell. (2005). p. 182–98.
22. Mohd Nor N, Steeneveld W, Mourits MCM, Hogeveen H. Estimating the costs of rearing young dairy cattle in the Netherlands using a simulation model that accounts for uncertainty related to diseases. *Pre Vet Med*. (2012) 106:214–24. doi: 10.1016/j.prevetmed.2012.03.004
23. Cheng AK. *Mathematical Modelling for Teachers*. New York, NY: Taylor & Francis Group. doi: 10.4324/9781351247979
24. Dijkhuizen AA, Huirne RBM, Jalvingh AW. Economic analysis of animal diseases and their control. *Prev Vet Med*. (1995) 25:135–49. doi: 10.1016/0167-5877(95)00535-8
25. Nurliyana M, Amal MNA, Zamri-Saad M, Ina-Salwany MY. Possible transmission routes of *Vibrio* spp. in tropical cage-cultured marine fishes. *Lett Appl Microbiol*. (2019) 68:485–96. doi: 10.1111/lam.13146
26. Ransangan J, Lal TM, Al-harbi AH. Characterization and experimental infection of *Vibrio harveyi* isolated from diseased Asian Seabass (*Lates calcarifer*). *Malays J Microbiol*. (2012) 8:104–15. doi: 10.21161/mjm.03512
27. Booth M, Alarcon J, Camper M, Jil SR, Meresse W, Ha DN, et al. *Validation of Commercial Feeds for Asian Seabass Containing Optimized Levels of Soybean Meal and Soy Protein Concentrate (Vietnam)*. (2015). Available online at: https://ussec.org/resources/validation-commercial-feeds-asian-seabass-optimized-levels-soybean-meal-soy-protein-concentrate-vietnam/ (accessed April 23, 2021).
28. Glencross BD, Bermudes M. Adapting bioenergetic factorial modelling to understand the implications of heat stress on barramundi (*Lates calcarifer*) growth, feed utilisation and optimal protein and energy requirements - potential strategies for dealing with climate change? *Aquac Nutr*. (2012) 18:411–22. doi: 10.1111/j.1365-2095.2011.00913.x
29. World sea temperature. *Malaysia Sea Temperature*. (2020). Available online at: https//www.seatemperature.org/asia/malaysia/ (accessed June 15, 2020).
30. Anil MK. Santosh B, Jasmine S, Saleela KN, George RM, Jose Kingsly H, et al. Growth performance of the seabass *Lates calcarifer* (Blotch) in sea cage at Vizhinjam Bay along the south-west coast of India. *Indian J Fish*. (2010) 57:65–9. Available online at: https://www.researchgate.net/publication/264042246 (accessed April 14, 2021).
31. Glencross B, Rutherford N, Hawkins W. Determining waste excretion parameters from barramundi aquaculture final report for aquaculture development fund of WA. *Fisheries Research Contract Report*. (2003). Available online at: http://www.fish.wa.gov.au/res (accessed April 27, 2021).
32. Tacon A, Rausin N, Kadari M, Cornelis P. The food and feeding of tropical marine fishes in floating net cages: Asian seabass, *Lates calcarifer* (Bloch), and brown-spotted grouper, *Epinephelus tauvina* (Forskal). *Aquac Res*. (1991) 22:165–82. doi: 10.1111/j.1365-2109.1991.tb00507.x
33. Department of Fisheries Malaysia (DOFM). *Steps Towards Biosecurity Fish Farm*. (2011). Available online at: http://www.dof.gov.my (accessed October 31, 2020).
34. Jerry DR. Biology and culture of Asian seabass *Lates calcarifer*. Boca Raton, FL: CRC Press (2014). doi: 10.1201/b15974
35. Sugita H, Yamamoto S, Asakura C, Morita T. Occurrence of *Listonella anguillarum* in seed production environments of Japanese flounder *Paralichthys olivaceus* (Temminck et Schlegel). *Aquac Res*. (2005) 36:920–6. doi: 10.1111/j.1365-2109.2005.01303.x

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.

Advantages of publishing in Frontiers

OPEN ACCESS
Articles are free to read for greatest visibility and readership

FAST PUBLICATION
Around 90 days from submission to decision

HIGH QUALITY PEER-REVIEW
Rigorous, collaborative, and constructive peer-review

TRANSPARENT PEER-REVIEW
Editors and reviewers acknowledged by name on published articles

Frontiers
Avenue du Tribunal-Fédéral 34
1005 Lausanne | Switzerland

Visit us: www.frontiersin.org
Contact us: frontiersin.org/about/contact

REPRODUCIBILITY OF RESEARCH
Support open data and methods to enhance research reproducibility

DIGITAL PUBLISHING
Articles designed for optimal readership across devices

FOLLOW US
@frontiersin

IMPACT METRICS
Advanced article metrics track visibility across digital media

EXTENSIVE PROMOTION
Marketing and promotion of impactful research

LOOP RESEARCH NETWORK
Our network increases your article's readership