THESIS

THE ANIMAL HEALTH COMPONENTS OF A BIOSURVEILLANCE SYSTEM

Submitted by

Alwyn Tan

Department of Clinical Sciences

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2023

Master's Committee:

Advisor: Mo Salman

Brian McCluskey

Susan VandeWoude

ABSTRACT

THE ANIMAL HEALTH COMPONENTS OF A BIOSURVEILLANCE SYSTEM

Biosurveillance defines a One Health approach of gathering, integrating, interpreting, and communicating information related to health hazards or diseases affecting human, animal, or plant health and their environment to achieve early detection and warning, situational awareness, and better decision making. Animal health surveillance is an important component within biosurveillance systems comprising a continuum of activities from detecting biological threats, to analyzing relevant data, to managing identified threats, and embracing a One Health concept.

Despite ongoing health surveillance activities conducted by various stakeholders in different One Health sectors, numerous health crises continue to occur, affecting the health of humans and animals, the livelihoods of people, the economy, their environment, and social harmony. Zoonotic agents caused a large proportion of these health crises, and nations spent large amounts of resources on disease detection and control measures to safeguard the health of their citizens against these agents.

This thesis will explore how the animal health community can strengthen biosurveillance in the following sections: 1) the components of a biosurveillance system from an animal health perspective and opportunities for the animal health surveillance community to enhance biosurveillance; 2) a pilot study on the use of air-sampling as a novel method for animal health surveillance; 3) a scoping review on behavioral barriers, enablers, and interventions for animal

owners and producers reporting animal diseases to veterinary authorities; and 4) theoretical demonstration of a biosurveillance system.

ACKNOWLEDGEMENTS

I would like to thank my adviser, Dr. Mo Salman, for his guidance and advice throughout my academic program, rigorous engagement in my learning journey, and network of valuable research opportunities. I would also like to thank my graduate committee members, Dr. Sue VandeWoude, and Dr. Brian McCluskey, for their helpful guidance and advice on my academic program and research projects.

A manuscript of Chapter 2 was published in a peer-reviewed journal, Agriculture, and this was made possible by the contributions of my co-authors Dr. Mo Salman, Dr. Bruce Wagner, and Dr. Brian McCluskey.

I would like to extend my gratitude to the BROADN project leadership and members for making my air-sampling pilot study possible. I especially thank Dr. Angela Bosco-Lauth for supervising this project, advice on designing this study, supporting the procurement of equipment and reagents, and reviewing and editing my report. I also thank Dr. Brad Borlee for his advice on designing this study, providing laboratory training, access to his BSL-2 laboratory for the processing and analysis of samples, and reviewing and editing my report. I also thank Dr. Thomas Hill, Dr. Marina Nieto-Caballero, Dr. Noelle Bryan, Dr. Paul Demott, and Dr. Sonia Kreidenweis for their advice on air-sampling methods, training, and access to the BioSamplers; Dr. Mark Hernandez for lending the BioSpot 300p Bioaerosol Samplers; Halley Pucker and Dr. Amr Ramadan for providing assistance in the field and laboratory; Christina Nash for facilitating access to ARDEC; Dr. Doreene Hyatt, Dr. Josh Daniels, Dr. Sue VandeWoude, and Dr. Mo Salman for advice on the design of this study,

For the scoping review, I am thankful to the USDA APHIS Center for Epidemiology and Animal Health and USDA National Agricultural Library for collaborating on this project. I especially thank Dr. Shana Gillette for supervising this project, developing the concept for this study, sharing knowledge and resources on social and behavioral science, participating as a reviewer in the pilot, refining the protocols, reviewing, and editing the report. I also thank Stephanie Ritchie, Elizabeth Tobey, and Jessica Sigman for advising on the protocols for the scoping review, developing and executing the search strategy for the full scoping review. I also thank Mary Foley for conducting the literature search that was used in the pilot. I thank Dr. Gillette and Dr. Deb Green for being independent reviewers in the pilot.

Finally, I am thankful to the National Parks Board of Singapore for sponsoring my studies and supporting my professional development. I thank Kenneth Er, Dr. Yap Him Hoo, Dr. Chua Tze Hoong, Dr. Kelvin Lim, Dr. Charlene Fernandez, Wong Wai Kwan, and my other colleagues in NParks for their support and continued engagement while I was overseas.

This thesis has been possible with the generous support of the wonderful people mentioned above.

PREFACE

All sections of this thesis comprise my original work toward the Degree of Master of Science in Clinical Sciences, except where detailed here.

A manuscript of Chapter 2 was published in a special issue of Agriculture on the theme of "Animal Diseases Surveillance Systems: Tools and Demonstrations". The title of the article was “The role of animal health components in a biosurveillance system: concept and demonstration” (https://doi.org/10.3390/agriculture13020457). I was the lead author, responsible for conceptualization, writing, editing, and creating diagrams. All co-authors were involved in conceptualization and editing. Dr. Brian McCluskey wrote the section on “data stream integration, processing, analysis, and access by decision makers”. Dr. Mo Salman co-created the diagrams.

A modified version of Chapter 4 was presented at The Wildlife Society 29th Annual Conference, held in Spokane, Washington, November 6-10, 2022. The title of the presentation and abstract was “Discovering the Aerobiome”. I was the presenter and author for the presentation and abstract. Dr. Angela Bosco-Lauth reviewed and edited the presentation and abstract.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

Introduction

1.1 General introduction

The One Health concept describes that human, animal, plant, and environmental health are closely linked and interdependent (World Health Organization, 2022). Approximately 60% of pathogens causing human disease and 75% of emerging human pathogens originate from animals. Furthermore, diseases in livestock pose a threat to the livelihoods of producers and disrupt food security as livestock are a major source of food (World Organisation for Animal Health, 2022b). In addition, plant diseases and pests may affect the availability and quality of crops for animal feed which in turn affect livestock yield (Rizzo et al., 2021).

Surveillance for public, animal, and plant health are essential for safeguarding One Health. Health surveillance activities across sectors generally include the collection of data, analysis of information, and taking action to control risks (IPPC Secretariat, 2021; World Health Organization, 2023; World Organisation for Animal Health, 2022a). Despite the existence of health surveillance systems operating at the global, national, and local levels, numerous environmental and socio-political challenges such as climate change, increased urbanization, globalization, and political conflicts, have highlighted potential limitations of existing surveillance programs.

Biosurveillance is a holistic approach that combines the surveillance of potential threats and diseases across human, animal, plant, and environmental health sectors. By integrating data from these different sources, it allows for more comprehensive collection, analysis and

interpretation of information, ultimately leading to improved decision making and enhanced protection for overall One Health (The White House, 2012).

This thesis focusses on biosurveillance from an animal health perspective, with the following underpinning research questions:

1. What are the components of a biosurveillance system?
2. How can animal health surveillance be enhanced to improve biosurveillance?

The review in Chapter 2 addresses a broad overview of the research questions, and the studies in Chapters 3 and 4 address specific components of enhancing biosurveillance. The demonstration in Chapter 5 illustrates the biosurveillance concepts presented in the prior chapters.

1.2 References

IPPC Secretariat. (2021). Surveillance guide – A guide to understand the principal requirements of surveillance programmes for national plant protection organizations. In (2nd ed.). Rome: FAO on behalf of the Secretariat of the International Plant Protection Convention.

Rizzo, D. M., Lichtveld, M., Mazet, J. A. K., Togami, E., & Miller, S. A. (2021). Plant health and its effects on food safety and security in a One Health framework: four case studies. *One Health Outlook*, *3*(1), 6. https://doi.org/10.1186/s42522-021-00038-7

The White House. (2012). *National Strategy For Biosurveillance*. Washington, DC, USA: The White House, Retrieved from https://obamawhitehouse.archives.gov/sites/default/files/National_Strategy_for_Biosurveillance_July_2012.pdf

World Health Organization. (2022). *One health*. World Health Organization. Retrieved September 21, 2022 from https://www.who.int/health-topics/one-health

World Health Organization. (2023). *Public health surveillance*. Retrieved January 28, 2023 from https://www.emro.who.int/health-topics/public-health-surveillance/index.html

World Organisation for Animal Health. (2022a). Glossary. In *Terrestrial Animal Health Code*. Paris, France: World Organisation for Animal Health.

World Organisation for Animal Health. (2022b). *One Health*. World Organisation for Animal Health. Retrieved September 14, 2022 from https://www.woah.org/en/what-we-do/global-initiatives/one-health/

Chapter 2

The role of animal health components in a biosurveillance system: concept and demonstration

2.1 Background

In 2001, letters containing anthrax spores were sent to people via the United States Postal Service, killing five people (U.S. Postal Inspection Service, 2021). In 2003, the outbreak of severe acute respiratory syndrome (SARS) spread to more than two dozen countries in Asia, Europe, North America and South America, killing 774 people (U.S. Centers for Disease Control and Prevention, 2017). Then, starting in 2019 and still ongoing as of writing this article, the COVID-19 pandemic resulted in the deaths of at least 6.49 million people worldwide and caused major disruptions to the lives of people (World Health Organization, 2022a). In addition to these three important health crises, there have been dozens of other recent biological incidences that have caused pain and suffering to the human population. There are several similarities between these health crises that were highlighted. Firstly, they were caused by zoonotic agents, meaning that infection can spread between humans and animals. Secondly, they not only affected the health of victims, but had adverse impact on the livelihoods of people, the economy, the environment, and social harmony. Thirdly, nations spent large amounts of resources on disease detection and control measures to safeguard the health of their citizens against these diseases.

Biosurveillance has been described as a system that enhances a country's ability to deal with the potential of natural and man-made biological threats. The United States National Strategy for Biosurveillance (The White House, 2012), defines biosurveillance as "the process of gathering, integrating, interpreting, and communicating essential information related to all-

hazards threats or disease activity affecting human, animal, or plant health to achieve early detection and warning, contribute to overall situational awareness of the health aspects of an incident, and to enable better decision making at all levels". The term biosurveillance emerged in the early 2000s in response to the need to enhance health surveillance systems due to potential bioterrorism threats. Following other threats of zoonotic epidemics during that decade, such as the SARS outbreak and H1N1 influenza pandemic, the scope of biosurveillance evolved to include diseases in animals and plants that may affect the wellbeing of humans (Kman & Bachmann, 2012; Nuzzo, 2017; Wagner, 2006a).

In the field of animal health, the World Organisation for Animal Health (WOAH) defines animal health surveillance as the systematic ongoing collection, collation, and analysis of information related to animal health and the timely dissemination of information so that action can be taken (World Organisation for Animal Health, 2022a).

Over the last two decades, there has been a growing literature on biosurveillance systems, with the majority focusing on reviewing or enhancing bioterrorism and public health surveillance. As the world is emerging from one of the most severe pandemics in recent times, there is strong motivation among countries to invest in biosurveillance to make improvements based on lessons learnt from COVID-19 and enhance biosurveillance programs to safeguard national interests. Consequently, consideration of how animal health surveillance fits into the system of biosurveillance and how enhancements to biosurveillance can benefit animal health surveillance is very timely.

The aim of this paper is to explore components of a biosurveillance system from an animal health perspective and identify opportunities for the animal health surveillance community to enhance biosurveillance.

2.2 The approach

A brief overview of biosurveillance and animal health surveillance is presented based on a narrative review of published literature, technical reports, and institutional websites. A detailed description of how biosurveillance fits into a national context with a focus on the contribution of animal health was then synthesized. Finally, some interesting developments that present opportunities for enhancing biosurveillance and animal health surveillance were highlighted.

2.3 Components of a biosurveillance system from an animal health perspective

2.3.1 Biosurveillance

The general components of a biosurveillance system are described by several publications which provided details on the process of data sources, data integration, analysis, and response (Huff et al., 2017; Kim & Tak, 2019; Wagner, 2006a). However, further detailed structures that provide a comprehensive illustration of the concepts of biosurveillance are few. Wagner (2006a) illustrated the systematic and process-oriented nature of a biosurveillance system (Figure 2.1). Both Wagner (2006a) and Kim and Tak (2019) provided illustrations of a biosurveillance process (Figure 2.2), which generally comprise collection and analyses of data from multiple sources on threats related to human, animal or plant health, with the goal of decision-making and response to the identified threat. However, the biosurveillance process illustrated by Wagner (2006a) (Figure 2.2a) only described the different components in the process, but the illustration by Kim

and Tak (2019) (Figure 2.2b) went further to describe multiple agencies and entities involved in the process.

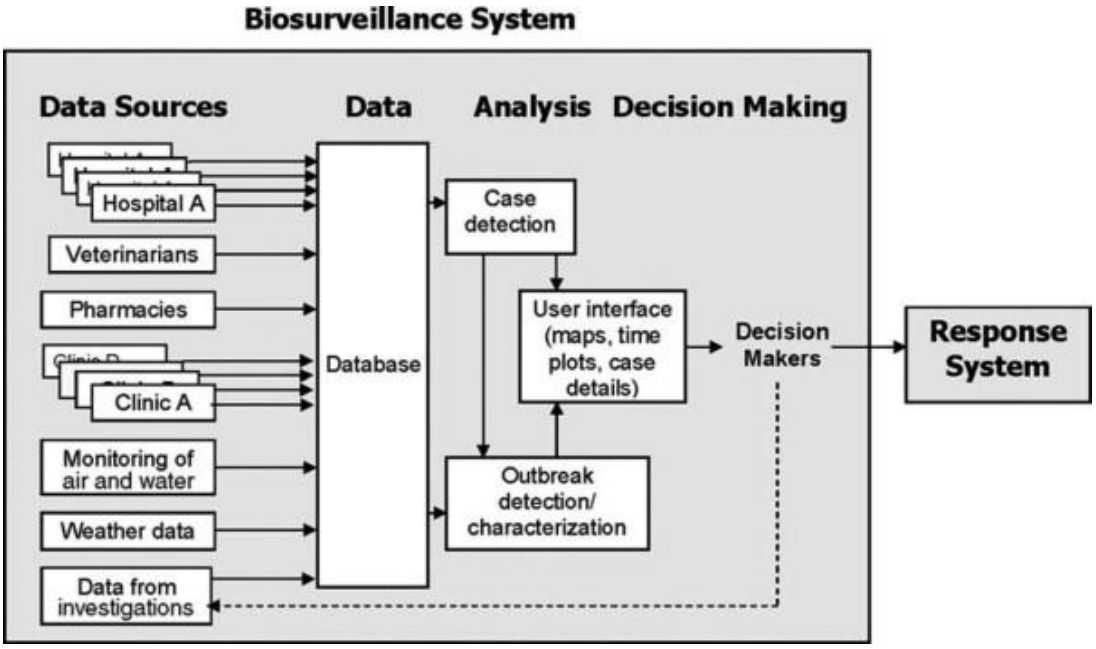
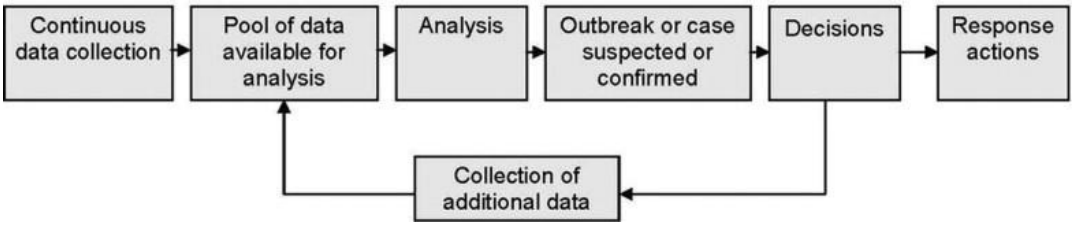


Figure 2.1. Diagram of biosurveillance system by Wagner (2006a).

(a)



(b)

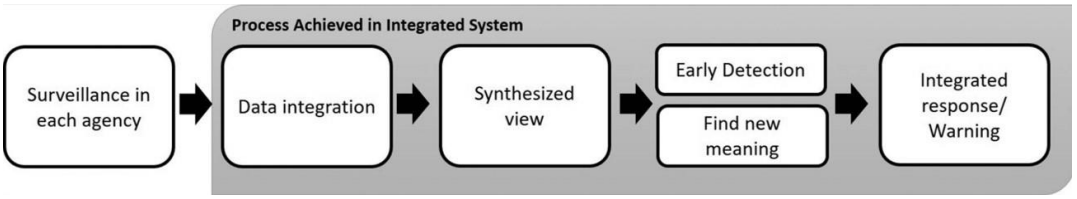


Figure 2.2. Diagram of biosurveillance process by (a) Wagner (2006a) and (b) Kim and Tak (2019).

The concept of One Health features prominently in the definition of biosurveillance. One Health refers to an integrated and unifying approach that aims to optimize and balance the health of people, animals, and the ecosystem in a sustainable way. The health of humans, animals, plants, and the environment are closely linked and interdependent. Hence, collaboration is required to develop holistic solutions and utilize the full spectrum of disease control to contribute to global health (World Health Organization, 2022c). Approximately 60% of pathogens causing human disease and 75% of emerging human pathogens originate directly or indirectly from animals. Furthermore, diseases in livestock pose a threat to food sustainability and the livelihoods of producers (World Organisation for Animal Health, 2022b).

Considering the essence and processes of a biosurveillance system, we designed a diagram to illustrate how a biosurveillance system fits in a national and One Health context (Figure 2.3). We introduce the combination of four components: policy, stakeholders, performance evaluation, and ecosystem, which we will elaborate on further in this article.

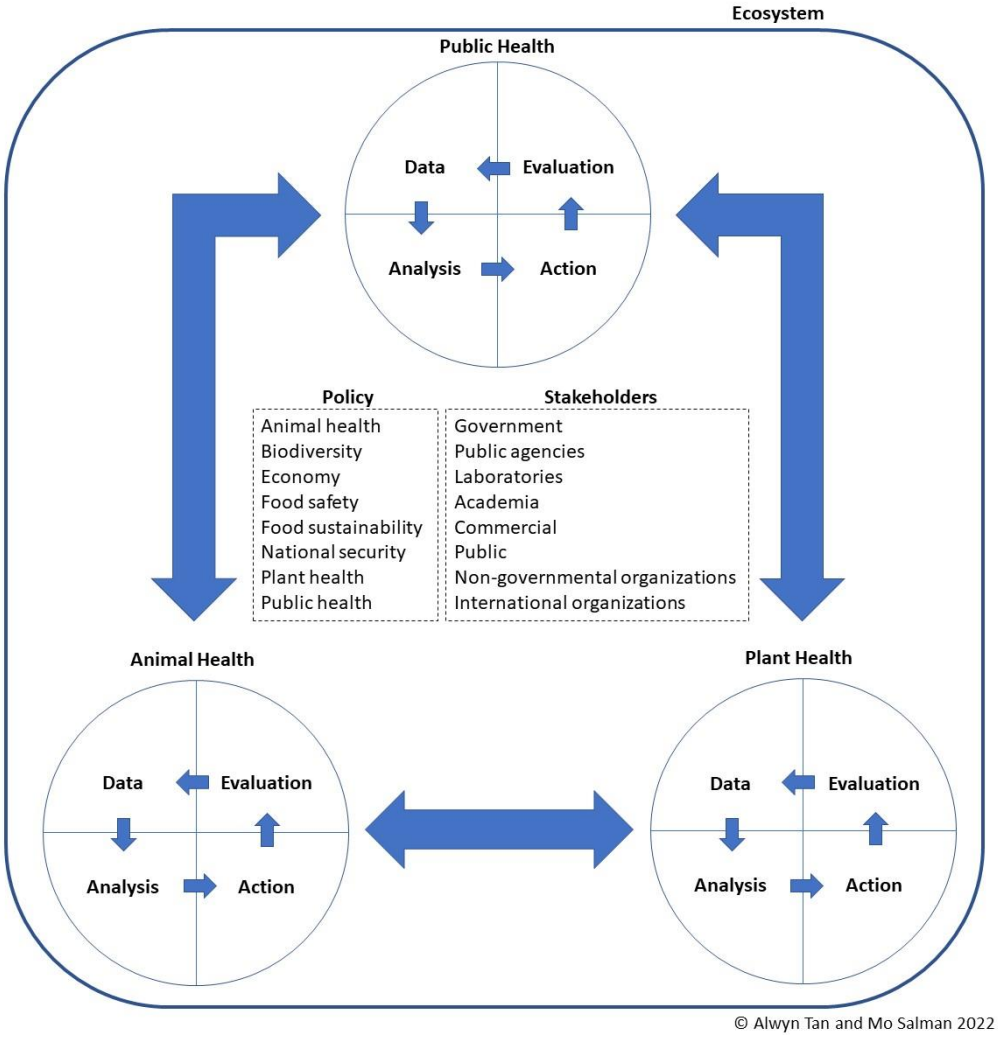


Figure 2.3. Components of a biosurveillance system under a One Health concept, showing the complementary relationships between components and One Health Sectors.

2.3.2 Animal health surveillance

The processes and objectives of animal health surveillance are a fully aligned subset of biosurveillance (Table 2.1). Both biosurveillance and animal health surveillance definitions describe data collection, analyses, and action. However, the scope of the data in animal health

surveillance is limited to animal health-related data, but the scope of data in biosurveillance encompasses human, animal, plant, and environmental health.

Table 2.1. Comparison of definitions of biosurveillance and animal health surveillance (The White House, 2012; World Organisation for Animal Health, 2022a).

	Data	Analysis	Action
Biosurveillance	Gathering, integrating, interpreting, and communicating essential information. Related to all-hazards threats or disease activity affecting human, animal, or plant health.	To achieve early detection and warning, contribute to overall situational awareness of the health aspects of an incident.	To enable better decision making at all levels.
Animal Health Surveillance	Systematic ongoing collection, collation, and the timely dissemination of information Related to animal health.	Analysis of information.	So that action can be taken.

Animal health surveillance is well described as a system where data are collected, analyzed and direct some form of action in response to the animal health event (Salman, 2003). For example, in the United States bovine tuberculosis surveillance program, inspection occurs at slaughterhouses to identify compatible lesions on bovine carcasses which can then be confirmed via laboratory tests. Infection-confirmed carcasses are traced back the herd of origin and affected herds are tested so that infected animals can be removed to eradicate bovine tuberculosis.

The four main surveillance objectives determine the type of data required to be collected. If a pathogen or agent is known to be present in the country, the first objective of surveillance can be to measure the frequency of disease to provide information for the design or evaluation of disease control measures. The second objective can be related to detect cases of infection or

disease to facilitate disease eradication measures. If a pathogen is absent from a country, the third objective of surveillance can be to demonstrate freedom from disease to be used as evidence for movement and market access for animal products, and the fourth objective can be early detection of a disease incursion so that measures can be taken to contain and eradicate the disease before it spreads. These four surveillance objectives and related actions align with the analysis and action components of biosurveillance, respectively. For more detailed discussions on the design of animal health surveillance systems, readers are directed to existing literature (Salman, 2003; World Organisation for Animal Health, 2021).

Considering the processes in a biosurveillance system, Figure 2.4 was designed to illustrate how an animal health surveillance system fits within a biosurveillance framework. The earth in the middle of the diagram reminds us that animal health surveillance occurs in a larger global or national context and is part of biosurveillance with relationships to surveillance in other One Health sectors.

Figure 2.4. Animal health surveillance activities illustrated under a biosurveillance framework.

One Health interdependencies, important for the success of animal health surveillance within a biosurveillance framework, can be demonstrated in several examples of One Health collaboration on data collection, analysis, and actions. Firstly, antimicrobial resistance (AMR) poses a threat to the effective treatment of diseases in humans, animals and plants and requires a collaborative effort by all One Health sectors to contribute to the surveillance of AMR. The quadripartite One Health Joint Plan of Action (Food and Agriculture Organization of the United

Nations et al., 2022) and Strategic Framework for Collaboration on Antimicrobial Resistance (World Health Organization et al., 2022) aim to provide guidance and support for nations to implement actions across sectors to preserve antimicrobial efficacy and equitable access to antimicrobials. The guidance includes developing surveillance on AMR and antimicrobial use and developing best practices on the prudent use of antimicrobials. Secondly, the United States National Biodefense Strategy and Implementation Plan (The White House, 2022) has the goal of countering biological threats, enhancing pandemic preparedness, and achieving global health security. The plan reflected on the limitations in biodefense capabilities with respect to the COVID-19 pandemic and emphasized the need for a One Health approach and multisectoral cooperation in the areas of communication, surveillance, preparedness, and response to biological incidents. Thirdly, although the COVID-19 pandemic is caused largely by human-to-human transmission, there has been an important One Health approach to surveillance for severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection in animals as animal reservoirs are a risk for emergence of new variants, zoonotic transmission to humans, and may affect the health and ecology of animal populations. During the early stages of the pandemic, research determined that multiple animal species, including cats, ferrets, hamsters, bats, non-human primates, and mink, were susceptible to SARS-CoV-2 and the WOAH recommended monitoring of infections in animals (Hobbs & Reid, 2021; World Organisation for Animal Health, 2020). More recently, a joint statement by the Food and Agricultural Organization of the United Nations (FAO), WOAH and World Health Organization (WHO) recommended that competent authorities prioritized the monitoring of SARS-CoV-2 infection in wildlife and prevent the formation of animal reservoirs (Food and Agriculture Organization et al., 2022). Fourthly, the Zero by 30 (global

strategic plan to end human deaths from dog-mediated rabies by 2030) demonstrates a One Health collaboration to reduce human deaths from a zoonotic disease (World Health Organization et al., 2018). While efforts are being made to increase the availability of vaccines and post-exposure prophylaxis to prevent infection and disease in humans, concurrent mass vaccination of dogs in rabies endemic countries is required to break the cycle of disease transmission. When successful, this One Health collaboration will improve the health of both humans and animals in the ecosystem. Fifthly, the United States Department of Health and Human Services established the Administration for Strategic Preparedness and Response to strengthen public health infrastructure and capabilities to coordinate a national response to disasters and emergencies (Administration for Strategic Preparedness & Response, 2022). Despite the organization's strong focus on medical resources, they have also included resources on the management of animals during disasters. This One Health approach of disaster management promotes the safety and recovery of families and their pets. Lastly, One Health collaboration was critical in detecting and controlling the largest Q fever outbreak affecting approximately 4,000 people in the Netherlands between 2007-2010. Public health authorities, animal health authorities, and farmers worked together to identify goat farms as the major source of infection, leading to interventions such as improving hygiene practices on farms and vaccinating goats which eventually controlled the outbreak (Schneeberger et al., 2014).

2.3.3 Policy

The link between the science of biosurveillance and public policy is important to ensure alignment of national objectives, adequate attention, and available resources. Hence, the policy component is drawn at the center of biosurveillance in Figure 2.3. Public policy is the sum of

government activities, pursued directly or through agents, that have an influence on the lives of citizens (Peters, 2018). In general, public policies are made in response to issues that require attention, decisions are made by governments on behalf of the public to take action or not to take action, and policies are implemented by the government or other public or private stakeholders to address the issue (Howlett et al., 2020). At any time, there are numerous agendas or issues competing for the attention of decision-makers and limited resources. This competition for attention means that the community involved in biosurveillance, that has direct benefits for public and animal health, must constantly demonstrate their importance to governments and citizens, and deliver positive impact on the lives of citizens.

Different countries may implement biosurveillance based on various policy priorities. For example, the United States National Strategy for Biosurveillance frames biosurveillance as a solution for national security (The White House, 2012), whereas the Australian Department of Agriculture, Fisheries and Forestry frames biosurveillance as a means to protect and develop a very important agriculture industry (Australia Department of Agriculture Fisheries and Forestry, 2021).

One example of policy driving other components of biosurveillance is demonstrated by the development and adoption of a geographical bovine spongiform encephalopathy (BSE) risk assessment method by the European Union in 1999 (Salman et al., 2012). When BSE was confirmed as a zoonotic disease in 1996, countries established trade barriers to livestock and other animal-related products. Determining which countries to trade with was complicated by the uncertainty of the epidemiology of the disease. The main challenge with BSE was the long incubation period in cattle (average of 5 years) and difficulty in detecting the disease

antemortem. Hence, it was difficult to determine the risk of BSE introduction from imports based on self-reporting of BSE cases by countries. With the objective of balancing trade with the need to protect human and animal health, the European Commission established the Scientific Steering Committee, which in turn established a Transmissible Spongiform Encephalopathies (TSE) ad hoc working group that comprised expert stakeholders from academia and government. The working group developed the geographical BSE risk assessment method that determined the likelihood of BSE infection presence in a country based on information on imports and the cattle farming system. Countries that participated in the risk assessment were classified on four levels of risk, ranging from highly unlikely to confirmed. A beneficial output of this risk assessment was that several countries that had not reported cases but were classified as BSE "cannot be excluded", intensified their surveillance and eventually confirmed cases, allowing them to take necessary disease control measures. Additionally, conditions for import to reduce the risk of BSE could be applied to facilitate trade with countries that did not report cases but did not have negligible risk. The success in implementing this policy was evident in improved surveillance for BSE and reduction in the spread of BSE. This risk assessment was also the framework for development of the WOAH recommended international standard for BSE risk assessment in the Terrestrial Animal Health Code.

Hence, with an understanding of how biosurveillance and animal health surveillance fit within changing national agendas, the animal health community will better align their activities to contribute to the benefit of citizens and guide the framing of advocacy in areas that require attention and resources.

2.3.4 Stakeholders

The range of stakeholders that participate in biosurveillance is broad, ranging from government authorities, to businesses, to the general public, and these stakeholders may come from one or multiple sectors in the One Health community. Similar to the policy alignment discussed earlier, stakeholder alignment is crucial for biosurveillance activities and hence the stakeholder component is also drawn at the center of biosurveillance in Figure 2.3.

A large proportion of biosurveillance work is typically carried out by the government or state agencies and laboratories involved in collecting biological samples for disease testing. Other stakeholders play important roles in biosurveillance, such as private physicians and veterinarians who provide services to treat and manage the health of their human and animal patients. Since they are first to diagnose diseases in individuals, they are also responsible for reporting confirmed or suspected notifiable diseases to the relevant authorities. Most medical records are now stored on digital information systems, and there is wide potential for the use of health data for national biosurveillance, although there may be barriers to the aggregation of data across institutions. Wagner and Hogan (2006) described the potential use and system challenges accessing human healthcare records for biosurveillance. Similar challenges exist in the veterinary sector, but one recent breakthrough is the development of the Veterinary Companion Animal Surveillance System (VetCompass) that collects anonymized records from the database of participating veterinary clinics and hospitals in the United Kingdom (O'Neill, 2012; Royal Veterinary College, 2022). The data on VetCompass has been used for veterinary research and there is potential for it to be used for biosurveillance, such as a syndromic surveillance data stream.

In addition, stakeholders from different communities likely will have inherently different technical abilities, political interests, social and cultural values, and objectives. Hence it is important that the participants in biosurveillance need to be able to identify with the objectives and benefits of biosurveillance to ensure their continued participation and success of the system. Participatory epidemiology encourages the involvement of animal owners who have localized knowledge and experience on animal disease as well as social and cultural context (Alders et al., 2020). Participants should be engaged in the planning, design, and implementation of the system. For example, Bordier et al. (2021) described a participatory approach to engaging stakeholders in designing One Health surveillance systems. The framework was utilized in the development of AMR and *Salmonella* surveillance programs in two countries, allowing diverse stakeholders to gain mutual understanding and expectations of the surveillance activities required. Additional examples of how participatory epidemiology was utilized to increase engagement of stakeholders in surveillance activities are presented in Alders et al. (2020).

The Swine Health Information Center (SHIC) and the Swine Health Monitoring Project (SHMP) are examples of different stakeholders in the swine industry working together for a common goal (Betlach et al., 2016; Swine Health Information Center, 2023). The SHMP started in 2011 as a collaboration between the United States pork industry, academic institutions, and government agencies, while the SHIC was created in 2015 to support the project. These stakeholders have come together to monitor the health of swine herds in the United States and respond to disease threats in a timely manner. This collaborative multi-stakeholder and multi-disciplinary approach to animal health surveillance brings together the expertise and resources of different stakeholders to address the disease challenges facing the swine industry. In another

example, several networks such as the Extension Disaster Education Network (EDEN), National Plant Diagnostic Network (NPDN), and National Animal Health Laboratory Network (NAHLN) comprising government agencies, academic institutions, industry organizations, and diagnostic laboratories, exist to raise awareness and facilitate diagnoses of emerging infectious diseases in animals and plants. This collaboration enhances early detection and rapid response efforts to protect animal health, plant health, and the community (Extension Disaster Education Network, 2018; U.S. Department of Agriculture, 2022b, 2023).

Stakeholder participation in biosurveillance can be strengthened through social science and behavioral methods Biosurveillance activities require the cooperation of stakeholders to participate in supporting resource allocation, providing data, and performing actions to control or reduce the risk of disease. Human behavior is not only influenced by scientific information, but depends on a myriad of social, cultural, and political factors.

Although COVID-19 vaccines have been scientifically proven to be effective at reducing COVID-19 infection, public confidence and acceptance of the vaccine was low in some segments of society. Evidence-based vaccination programs meant to protect citizens against COVID-19 disease were insufficient to overcome misinformation or distrust of some experts (Rosenbaum, 2021). According to the World Health Organization and United Nations Children's Fund (2021), the behavioral and social drivers that affect vaccine uptake are what people think and feel about vaccines, social processes that drive or inhibit vaccination, individual motivation or hesitancy, and practical factors in seeking and receiving vaccination. Social and behavioral sciences are commonly used to study public health barriers and design interventions to improve health. Piltch-Loeb and DiClemente (2020) describe studying population characteristics of social class, culture,

ethnicity, individual beliefs, attitudes and behaviors, and cultural and socio-political systems that can affect public health threats and solutions in the case of vaccine hesitancy.

In animal health surveillance, similar social and behavioral factors affect the success of biosurveillance goals. Firstly, a study of knowledge and attitudes of Australian livestock producers on biosecurity practices found that improving producers' knowledge on biosecurity methods may increase their willingness to implement biosecurity practices, but the lack of communication from agricultural, veterinary or government organizations may be barriers to biosecurity practices (Paquette et al., 2020). Secondly, disease reporting is an important data stream for early detection of disease in livestock, but farmers are believed to be underreporting diseases. Studies found that barriers to disease reporting by farmers include uncertainty about clinical signs of diseases, fear of social and economic consequences, negative beliefs on response measures, mistrust of animal health authorities, lack of incentives, and unawareness of reporting procedures (Gates et al., 2021). Hence, solutions to these behavioral barriers should adopt theories and methods from social sciences and behavioral methods to address the different identities, motivations, and beliefs of stakeholders.

2.3.5 Data streams

Data streams for biosurveillance can be classified as traditional or non-traditional sources, and are based on the objectives of biosurveillance (Margevicius et al., 2014). Velikina et al. (2006) described potential traditional data streams to include notifiable disease reports by physicians and veterinarians, laboratory test results confirming disease, hospital records, livestock farming records, water supply testing results, and food and pharmaceutical industry records. Non-traditional and newer types of surveillance data include sales of over-the-counter medicines,

chief complaint of patients seeking medical care, absenteeism rates at the workplace or schools, internet activity and remote sensors monitoring physiological conditions of patients, animals, or environmental conditions. These non-traditional sources may also be called pre-diagnostic information or syndromic data, as they do not directly measure cases of specific diseases and can contain an outbreak signal earlier than traditional data sources (Shmueli & Burkom, 2010). Further types of data that may be utilized for biosurveillance include data associated with disease risk factors such as air and water quality measurements (Shmueli & Burkom, 2010).

Earlier methods of evaluating biosurveillance data were primarily based on ability of data to contribute to early detection of outbreaks, data availability, and cost of acquiring the data (Wagner, 2006b). However, biosurveillance has broader goals that include early warning of threats which precede any outbreak. Hence, disease reporting systems and laboratory test results, whilst being highly effective for the purpose of early disease detection or situational awareness, are not able to achieve the goal of early threat warning. To achieve the full spectrum of goals for biosurveillance, data streams from syndromic surveillance and environmental surveillance are required from across the One Health sectors (Margevicius et al., 2014).

Margevicius et al. (2014) described a framework for the evaluation of biosurveillance data streams based on the disease of interest, population, type of data (diagnostic, syndromic or environmental), categories (e.g., laboratory records, social media, sales) and whether they can achieve biosurveillance goals. The requirements to elevate a biosurveillance system from providing situational awareness to early warning is further explained by Velsko and Bates (2016) who described that in addition to traditional data sources such as disease reporting, syndromic surveillance data must be an automated component of a biosurveillance system.

One interesting environmental data stream for biosurveillance that is receiving renewed attention is the use of air samples to monitor for specific microorganisms and chemicals. The surveillance of air for biological threats is not new. For example, the BioWatch program by the United States Department of Homeland Security deploys air sampling devices in major cities to test for biological agents such as *Bacillus anthracis*, *Yersinia pestis*, and the smallpox virus (U.S. Department of Homeland Security, 2020; Wagner et al., 2006). Air-sampling surveys of zoonotic poultry diseases have also been conducted, where exotic Newcastle disease and highly pathogenic avian influenza were detected in air samples collected at infected poultry facilities (Hietala et al., 2005; Torremorell et al., 2016). However, there are gaps in the understanding of how bioaerosols are emitted, dispersed and deposited in the outdoor atmosphere, and ongoing research may provide more context for air surveillance to be used as a data stream in biosurveillance (BROADN, 2021; Global Atmospheric Microbiome Project, 2020; Mainelis, 2020; Šantl-Temkiv et al., 2020). For example, a study by Champion et al. (2002) found that the disposal of foot and mouth disease (FMD) infected cattle carcasses by burning was unlikely a risk of airborne spread of FMD virus to other farms. However, a more recent environmental study by Moore et al. (2021) found that wildland fires emitted high concentrations of microbes to the atmosphere, and the burning of dead vegetation contained more microbes than fresh vegetation. Although this study was from the environmental sciences sector, the atmospheric mechanisms of bioaerosols from burning of vegetation indicates an opportunity for further research related to animal pathogen dispersion.

2.3.6 Data stream integration, processing, analysis, and access by decision makers

The collection of data for animal health surveillance is followed by prescribed and directed actions in response to exceeding a pre-determined threshold or the detection of an animal health event. Additionally, the numerous and varied data streams mentioned in the previous section must be transformed into information that can be converted into knowledge for decision makers. Dórea and Revie (2021) suggested that implementing data driven surveillance frameworks is a three-step process including data integration, data processing to generate information, and data analysis creating accessible outputs for decision-makers.

Data integration is challenging due to the volume and variability of data that are almost ubiquitously captured in non-standardized formats (Gates et al., 2015). Efforts at standardizing the data elements collected by syndromic surveillance systems, laboratory information management systems and national herd and animal identification systems have been almost universally unsuccessful (Council for Agricultural Science and Technology, 2022). One notable success is the creation in the U.S. of a standard for electronic certificate of veterinary inspection data that is now transmitted between traceability systems facilitating more rapid and accurate disease tracing efforts (American Association of Veterinary Laboratory Diagnosticians & United States Animal Health Association, 2022). Without standardized data, extensive efforts to cleanse and transform data are required to facilitate analysis. Estberg et al. (2022) reported on enhancing surveillance through improved processing and integration of data. Automation of omitting and flagging duplicate reports or reports with errors along with an integrated data pipeline that automatically combines results from disparate data streams into a single dataset have significantly impacted the accuracy of reporting on equine infectious anemia findings in the U.S.

Leading edge software developments have revolutionized how data can be consumed, integrated, and used to inform decision-makers. With appropriate software, “organizations can clean, harmonize, and de-duplicate disparate data from across systems into a central, usable data layer for a single “source of truth” to improve care for population segments” (Palantir Technologies, 2022).

Leveraging biosurveillance streams for early threat detection requires innovative analytical and visualization methods. Syndromic surveillance research has focused on algorithms capable of detecting disease outbreak signals (Dórea et al., 2013). Shewhart control charts, exponentially weighted moving averages (EWMA) control charts and Holt-Winters exponential smoothing have been investigated for their value in improving early detection of events from syndromic surveillance streams. A freely available R package, Vetsyn, includes the aforementioned algorithms and ability to perform retrospective analyses of syndromic surveillance data (Dórea et al., 2015). This package aids epidemiologists and others responsible for implementing syndromic surveillance in leveraging data for early warnings. Odoi et al. (2009) developed an automated early warning system that used the prospective space-time permutations scan statistic. The system was tested against data on equine abortions and found that abortion outbreaks could be detected one week earlier than through traditional surveillance systems.

The outputs from these analyses need to be presented to decision makers quickly and in visual formats that are easily accessible. Many government entities responsible for animal health surveillance have moved away from written analysis reports of surveillance activities to disease dashboards or other near real-time visualizations. An excellent example of the dashboard

approach to result reporting is the United State Department of Agricultures (USDA) dashboard on detections of highly pathogenic avian influenza in wild birds (U.S. Department of Agriculture, 2022a). This specific USDA dashboard is available to the public, but other dashboards are restricted to use by regulatory decision makers (e.g., African swine fever and classical swine fever surveillance for field operations).

2.3.7 Surveillance evaluation

The ideal biosurveillance system is effective at achieving goals, efficient in the use of resources, and sustainable with time and emerging challenges. However, it is unlikely that such an ideal system exists based on the discussions in previous sections. Firstly, policymakers are making decisions and prioritizing between competing issues, with finite resources. Hence, biosurveillance programs may not be allocated the desired resources while remaining accountable to policymakers for the promised outcomes or goals. Secondly, there are many different stakeholders involved in providing data and performing actions in biosurveillance, and each stakeholder may bear different individual technical abilities, political interests, social and cultural values, which may affect the performance of a biosurveillance system. Thirdly, the myriad of traditional and non-traditional data streams in biosurveillance must not only contribute to achieving the biosurveillance goal, but also be available, practical, and not cost prohibitive.

Biosurveillance systems are vulnerable to external challenges. For example, the performance of a biosurveillance system that relies heavily on human resources may be severely impacted due external factors such as occurred in the “Great Resignation” in 2021 (Parker & Horowitz, 2022). Also, components of biosurveillance that involve laboratory testing may be adversely affected if laboratory equipment supply chains are disrupted, which happened during

the COVID-19 pandemic when laboratories faced shortages of equipment required to carry out diagnostic tests for COVID-19 itself and other disease surveillance (Woolston, 2021).

Biosurveillance evaluation can be used to overcome the sometimes unseen challenges of biosurveillance described above. Evaluation determines the merits of a surveillance system to achieve its goals, through a transparent, objective and evidence-based process, and provides recommendations on the system (Peyre, Goutard, et al., 2022).

The WHO has developed the Joint External Evaluation (JEE) tool to evaluate the public health capacities; and WOAH has developed the Performance of Veterinary Service (PVS) tool to evaluate the capacities of veterinary services respectively (World Health Organization, 2022b; World Organisation for Animal Health, 2019). These evaluation tools can be used internally (i.e., self-evaluation) or by an external independent expert evaluation team to evaluate the overall public health and veterinary service capacity of a country in accordance with international standards. Both the JEE and PVS include the evaluation of surveillance systems for diseases of importance to public and animal health and a higher capacity is recognized when countries perform regular evaluation on the performance of their surveillance systems.

Drewe et al. (2012) however, found that there were no standardized and consistent methods of evaluating human and animal health surveillance systems and comprehensive evaluations were uncommon. The U.S. Centers for Disease Control and Prevention (CDC) Guidelines for Evaluating Public Health Surveillance Systems was often used to evaluate biosurveillance systems (German et al., 2001; Groseclose & Buckeridge, 2017; Margevicius et al., 2014). However, there may be limitations when evaluation methods developed for public health

surveillance are applied to animal health or biosurveillance. Firstly, the evaluation of acceptability of the surveillance system differs between human and animal health. Acceptability is defined as the willingness of a person or organization to participate in the surveillance system (German et al., 2001; Peyre, Salman, et al., 2022). In the public health surveillance context, acceptability focusses on the willingness of stakeholders to report data, whereas in the animal health surveillance context, it focusses on both the willingness of stakeholders to report data as well as their beliefs on actions that may be taken such as the movement restrictions, culling, and compensation of diseased animals. Secondly, the evaluation of resource efficiency in human health surveillance focusses on cost-effectiveness, but in animal health surveillance, there is the option for cost-benefit analysis. This option arises because saving a human life is universally accepted and there are no alternatives while the value of animals can be determined. Hence, a utilitarian approach is adopted when considering animal health as there are viable alternative benefits for society on the use of resources. For example, the cost and benefit to society can be compared between improving livestock production through animal health measures or improving transportation by building roads.

Recently, Peyre, Schulz, et al. (2022) prescribed a comprehensive surveillance evaluation tool (EVA Survtool) that is applicable to both animal and human health surveillance, and, hence, biosurveillance. This tool allows the integrated evaluation of multiple attributes related to the effectiveness, efficiency, and sustainability of biosurveillance. In a case study, the EVA Survtool was used to evaluate a swine disease surveillance system in Vietnam (Peyre, Schulz, et al., 2022). The study found that pig farmers had higher acceptability if selective culling was utilized instead of 100% culling of infected pigs. The timeliness of reporting by farmers and sensitivity of

detecting diseased pigs increased when a higher compensation was paid for culled pigs. Although combining selective culling and high compensation was technically most effective at detecting and controlling pig disease, a cost-benefit analysis revealed that selective culling with a moderate compensation gave the highest benefit-cost ratio. This evaluation identified improvements to the surveillance system for pig diseases that would be acceptable technically and optimize the use of resources.

2.4 Conclusion

The threat to the health of people, animals, and the ecosystem by the ongoing COVID-19 pandemic and other animal diseases requires immediate attention from the global health community. With rising awareness of the One Health Concept by policy makers and the public, there is a golden opportunity for the global health community to promote and demonstrate effective One Health actions through a biosurveillance system. Integration of biosurveillance components is essential for building effective strategies to manage diseases, including preparedness for future pandemics. The animal health and veterinary professions have a major role in the biosurveillance system and can lead this effort by dedicating funding and resources to biosurveillance for global health. This effort, however, involves commitment from national and international leaders in the animal health and veterinary profession to work together under one goal – promotion of food sustainability, health, and wellbeing of the community at large.

2.5 References

Administration for Strategic Preparedness & Response. (2022). *About ASPR*. U.S. Department of Health & Human Services. Retrieved September 25, 2022 from https://aspr.hhs.gov/AboutASPR/Pages/default.aspx

Alders, R. G., Ali, S. N., Ameri, A. A., Bagnol, B., Cooper, T. L., Gozali, A., Hidayat, M. M., Rukambile, E., Wong, J. T., & Catley, A. (2020). Participatory Epidemiology: Principles, Practice, Utility, and Lessons Learnt [Review]. *Frontiers in Veterinary Science*, *7*. https://doi.org/10.3389/fvets.2020.532763

American Association of Veterinary Laboratory Diagnosticians, & United States Animal Health Association. (2022). *eCVI Data Exchange Standard*. Retrieved December 7, 2022 from https://github.com/AAVLD-USAHA-ITStandards/eCVI

Australia Department of Agriculture Fisheries and Forestry. (2021). *Agricultural Competitiveness White Paper – Biosecurity Surveillance and Analysis*. Australia Department of Agriculture, Fisheries and Forestry. Retrieved September 14, 2022 from https://www.agriculture.gov.au/biosecurity-trade/policy/agwhitepaper-bio-surveillance-analysis

Betlach, C., Baldry, H., Homann, T., VanderWaal, K., Kanankege, K., & Morrison, B. (2016). *Swine Health Monitoring Project serving as swine disease surveillance system*. Retrieved February 3, 2023 from https://www.nationalhogfarmer.com/health/swine-health-monitoring-project-serving-swine-disease-surveillance-system

Bordier, M., Goutard, F. L., Antoine-Moussiaux, N., Pham-Duc, P., Lailler, R., & Binot, A. (2021). Engaging Stakeholders in the Design of One Health Surveillance Systems: A Participatory Approach [Original Research]. *Frontiers in Veterinary Science*, *8*. https://doi.org/10.3389/fvets.2021.646458

BROADN. (2021). *BROADN: Aerobiome Research*. Retrieved September 29, 2022 from https://broadn.colostate.edu/research/

Champion, H. J., Gloster, J., Mason, I. S., Brown, R. J., Donaldson, A. I., Ryall, D. B., & Garland, A. J. M. (2002). Investigation of the possible spread of foot-and-mouth disease virus by the burning of animal carcases on open pyres. *Veterinary Record*, *151*(20), 593-600. https://doi.org/10.1136/vr.151.20.593

Council for Agricultural Science and Technology. (2022). *Zoonotic Diseases in Animal Agriculture and Beyond: A One Health Perspective* (Special Publication, Issue 33).

Dórea, F. C., & Revie, C. W. (2021). Data-Driven Surveillance: Effective Collection, Integration, and Interpretation of Data to Support Decision Making. *Frontiers in Veterinary Science*, *8*, 633977-633977. https://doi.org/10.3389/fvets.2021.633977

Dórea, F. C., Revie, C. W., McEwen, B. J., McNab, W. B., Kelton, D., & Sanchez, J. (2013). Retrospective time series analysis of veterinary laboratory data: Preparing a historical baseline for cluster detection in syndromic surveillance. *Preventive Veterinary Medicine*, *109*(3-4), 219-227. https://doi.org/10.1016/j.prevetmed.2012.10.010

Dórea, F. C., Widgren, S., & Lindberg, A. (2015). Vetsyn: An R package for veterinary syndromic surveillance. *Preventive Veterinary Medicine*, *122*(1-2), 21-32. https://doi.org/10.1016/j.prevetmed.2015.10.002

Drewe, J. A., Hoinville, L. J., Cook, A. J. C., Floyd, T., & Stärk, K. D. C. (2012). Evaluation of animal and public health surveillance systems: a systematic review. *Epidemiology and Infection*, *140*(4), 575-590. https://doi.org/10.1017/S0950268811002160

Estberg, L., Luxton, J., Spiegel, K., Pelzel-McCluskey, A., Gomez, B. L., & Vanden Eng, J. L. (2022). Business-centric data solutions for safeguarding American animal agriculture *World Organisation for Animal Health Scientific and Technical Review*, *41*(2).

Extension Disaster Education Network. (2018). *Structure*. Retrieved February 3, 2023 from https://extensiondisaster.net/about/structure/

Food and Agriculture Organization, World Organisation for Animal Health, & World Health Organization. (2022). *Joint statement on the prioritization of monitoring SARS-CoV-2 infection in wildlife and preventing the formation of animal reservoirs* https://www.who.int/news/item/07-03-2022-joint-statement-on-the-prioritization-of-monitoring-sars-cov-2-infection-in-wildlife-and-preventing-the-formation-of-animal-reservoirs

Food and Agriculture Organization of the United Nations, United Nations Environment Programme, World Health Organization, & World Organisation for Animal Health. (2022). *One health joint plan of action (2022–2026): working together for the health of humans, animals, plants and the environment*. (924005913X). Rome, Italy: Food and Agriculture Organization of the United Nations; United Nations Environment Programme; World Health Organization; World Organisation for Animal Health

Gates, M. C., Earl, L., & Enticott, G. (2021). Factors influencing the performance of voluntary farmer disease reporting in passive surveillance systems: A scoping review [Review]. *Preventive Veterinary Medicine*, *196*, 11, Article 105487. https://doi.org/10.1016/j.prevetmed.2021.105487

Gates, M. C., Holmstrom, L. K., Biggers, K. E., & Beckham, T. R. (2015). Integrating novel data streams to support biosurveillance in commercial livestock production systems in developed countries: challenges and opportunities. *Frontiers in public health*, *3*, 74-74. https://doi.org/10.3389/fpubh.2015.00074

German, R. R., Lee, L. M., Horan, J. M., Milstein, R. L., Pertowski, C. A., & Waller, M. N. (2001). Updated guidelines for evaluating public health surveillance systems: recommendations from the Guidelines Working Group. *MMWR Recomm. Rep.*, 1-35.

Global Atmospheric Microbiome Project. (2020). *The Global Atmospheric Microbiome Project*. Retrieved September 26, 2022 from http://atmospheric-microbiome.com/about/about_gamp.html

Groseclose, S. L., & Buckeridge, D. L. (2017). Public Health Surveillance Systems: Recent Advances in Their Use and Evaluation. *Annual Review of Public Health*, *38*(1), 57-79. https://doi.org/10.1146/annurev-publhealth-031816-044348

Hietala, S. K., Hullinger, P. J., Crossley, B. M., Kinde, H., & Ardans, A. A. (2005). Environmental air sampling to detect exotic Newcastle disease virus in two California commercial poultry flocks. *Journal of veterinary diagnostic investigation*, *17*(2), 198-200. https://doi.org/10.1177/104063870501700219

Hobbs, E. C., & Reid, T. J. (2021). Animals and SARS-CoV-2: Species susceptibility and viral transmission in experimental and natural conditions, and the potential implications for

community transmission. *Transboundary and Emergerging Diseases*, *68*(4), 1850-1867. https://doi.org/10.1111/tbed.13885

Howlett, M., Ramesh, M., & Perl, A. (2020). *Studying Public Policy: Principles and Processes* (4 ed.). Oxford University Press.

Huff, A. G., Allen, T., Whiting, K., Williams, F., Hunter, L., Gold, Z., Madoff, L. C., & Karesh, W. B. (2017). Biosurveillance: a systematic review of global infectious disease surveillance systems from 1900 to 2016. *Scientific & Technical Review*, *36*, 513-524. https://doi.org/https://doi.org/10.20506/rst.36.2.2670

Kim, A. J., & Tak, S. (2019). Implementation System of a Biosurveillance System in the Republic of Korea and Its Legal Ramifications. *Health Security*, *17*(6), 462-467. https://doi.org/10.1089/hs.2019.0071

Kman, N. E., & Bachmann, D. J. (2012). Biosurveillance: A Review and Update. *Advances in preventive medicine*, *2012*, 301408-301409. https://doi.org/10.1155/2012/301408

Mainelis, G. (2020). Bioaerosol sampling: Classical approaches, advances, and perspectives. *Aerosol science and technology*, *54*(5), 496-519. https://doi.org/10.1080/02786826.2019.1671950

Margevicius, K. J., Generous, N., Taylor-McCabe, K. J., Brown, M., Daniel, W. B., Castro, L., Hengartner, A., & Deshpande, A. (2014). Advancing a framework to enable characterization and evaluation of data streams useful for biosurveillance. *PLOS ONE*, *9*(1), e83730. https://doi.org/10.1371/journal.pone.0083730

Moore, R. A., Bomar, C., Kobziar, L. N., & Christner, B. C. (2021). Wildland fire as an atmospheric source of viable microbial aerosols and biological ice nucleating particles. *The ISME Journal*, *15*(2), 461-472. https://doi.org/10.1038/s41396-020-00788-8

Nuzzo, J. B. (2017). Improving Biosurveillance Systems to Enable Situational Awareness During Public Health Emergencies. *Health Security*, *15*(1), 17-19. https://doi.org/10.1089/hs.2016.0097

O'Neill, D. (2012). VetCompass clinical data points the way forward. *Veterinary Ireland Journal*, *2*(7), 353-356.

Odoi, A., Carter, C. N., Riley, J. W., Smith, J. L., & Dwyer, R. M. (2009). Application of an automated surveillance-data-analysis system in a laboratory-based early-warning system for detection of an abortion outbreak in mares. *American journal of veterinary research*, *70*(2), 247-256. https://doi.org/10.2460/ajvr.70.2.247

Palantir Technologies. (2022). *Foundry for Population Health*. Retrieved December 7, 2022 from https://www.palantir.com/assets/xrfr7uokpv1b/7EzTCn3cz13pTAx8u3U5WM/29ae2623771441b61b2f7267b6f47789/Foundry_for_Population_Health.pdf

Paquette, C., Schemann, K., & Ward, M. (2020). Knowledge and attitudes of Australian livestock producers concerning biosecurity practices. *Australian Veterinary Journal*, *98*(11), 533-545. https://doi.org/https://doi.org/10.1111/avj.13005

Parker, K., & Horowitz, J. M. (2022). *Majority of workers who quit a job in 2021 cite low pay, no opportunities for advancement, feeling disrespected*. Pew Research Center. Retrieved September 27, 2022 from https://www.pewresearch.org/fact-tank/2022/03/09/majority-of-workers-who-quit-a-job-in-2021-cite-low-pay-no-opportunities-for-advancement-feeling-disrespected/

Peters, B. G. (2018). *American public policy: Promise and performance* (11 ed.). SAGE Publications.

Peyre, M., Goutard, F., & Roger, F. (2022). Why Do We Need to Evaluate Health Surveillance Systems? In Marisa Peyre, François Roger, & Flavie Goutard (Eds.), *Principles for Evaluation of One Health Surveillance: The EVA Book* (pp. 3-24). Springer Nature Switzerland AG.

Peyre, M., Salman, M., & Steneroden, K. (2022). Frameworks and Tools for Evaluating Health Surveillance Systems. In Marisa Peyre, François Roger, & Flavie Goutard (Eds.), *Principles for Evaluation of One Health Surveillance: The EVA Book* (pp. 43-60). Springer Nature Switzerland AG.

Peyre, M., Schulz, K., Pham, T. T. H., & Häsler, B. (2022). The EVA Survtool: An Integrated Framework to Plan Health Surveillance Evaluation. In Marisa Peyre, François Roger, & Flavie Goutard (Eds.), *Principles for Evaluation of One Health Surveillance: The EVA Book* (pp. 61-92). Springer Nature Switzerland AG.

Piltch-Loeb, R., & DiClemente, R. (2020). The Vaccine Uptake Continuum: Applying Social Science Theory to Shift Vaccine Hesitancy. *Vaccines*, *8*(1), 1. https://doi.org/10.3390/vaccines8010076

Rosenbaum, L. (2021). Escaping Catch-22 — Overcoming Covid Vaccine Hesitancy. *The New England journal of medicine*, *384*(14), 1367-1371. https://doi.org/10.1056/NEJMms2101220

Royal Veterinary College. (2022). *About VetCompass*. Retrieved Sep 22, 2022 from https://www.rvc.ac.uk/vetcompass/about/overview

Salman, M., Silano, V., Heim, D., & Kreysa, J. (2012). Geographical BSE risk assessment and its impact on disease detection and dissemination. *Preventive Veterinary Medicine*, *105*(4), 255-264. https://doi.org/https://doi.org/10.1016/j.prevetmed.2012.01.006

Salman, M. D. (2003). *Animal disease surveillance and survey systems : methods and applications* (1st ed.). Iowa State Press. https://doi.org/10.1002/9780470344866

Šantl-Temkiv, T., Sikoparija, B., Maki, T., Carotenuto, F., Amato, P., Yao, M., Morris, C. E., Schnell, R., Jaenicke, R., Pöhlker, C., DeMott, P. J., Hill, T. C. J., & Huffman, J. A. (2020). Bioaerosol field measurements: Challenges and perspectives in outdoor studies. *Aerosol science and technology*, *54*(5), 520-546. https://doi.org/10.1080/02786826.2019.1676395

Schneeberger, P. M., Wintenberger, C., van der Hoek, W., & Stahl, J. P. (2014). Q fever in the Netherlands – 2007–2010: What we learned from the largest outbreak ever. *Médecine et Maladies Infectieuses*, *44*(8), 339-353. https://doi.org/https://doi.org/10.1016/j.medmal.2014.02.006

Shmueli, G., & Burkom, H. (2010). Statistical Challenges Facing Early Outbreak Detection in Biosurveillance. *Technometrics*, *52*(1), 39-51. https://doi.org/10.1198/TECH.2010.06134

Swine Health Information Center. (2023). *Plan of Work*. Retrieved February 3, 2023 from https://www.swinehealth.org/plan-of-work/

The White House. (2012). *National Strategy For Biosurveillance*. Washington, DC, USA: The White House, Retrieved from https://obamawhitehouse.archives.gov/sites/default/files/National_Strategy_for_Biosurveillance_July_2012.pdf

The White House. (2022). *National Biodefense Strategy and Implementation Plan*. Washington, DC, USA: The White House Retrieved from https://www.whitehouse.gov/wp-content/uploads/2022/10/National-Biodefense-Strategy-and-Implementation-Plan-Final.pdf

Torremorell, M., Alonso, C., Davies, P. R., Raynor, P. C., Patnayak, D., Torchetti, M., & McCluskey, B. (2016). Investigation into the Airborne Dissemination of H5N2 Highly Pathogenic Avian Influenza Virus During the 2015 Spring Outbreaks in the Midwestern United States. *Avian Diseases*, *60*(3), 637-643. https://doi.org/10.1637/11395-021816-Reg.1

U.S. Centers for Disease Control and Prevention. (2017). *SARS Basics Fact Sheet*. U.S. Centers for Disease Control and Prevention. Retrieved September 14, 2022 from https://www.cdc.gov/sars/about/fs-sars.html

U.S. Department of Agriculture. (2022a). *2022 Detections of Highly Pathogenic Avian Influenza in Wild Birds*. Retrieved December 12, 2022 from https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/animal-disease-information/avian/avian-influenza/hpai-2022/2022-hpai-wild-birds

U.S. Department of Agriculture. (2022b). *About NAHLN*. Retrieved February 3, 2023 from https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/lab-info-services/nahln/

U.S. Department of Agriculture. (2023). *National Plant Diagnostic Network*. Retrieved February 3, 2023 from https://www.nifa.usda.gov/national-plant-diagnostic-network

U.S. Department of Homeland Security. (2020). *Detecting Bioterrorist Attacks*. United States Department of Homeland Security. Retrieved September 26, 2022 from https://www.dhs.gov/biowatch-program

U.S. Postal Inspection Service. (2021, Nov 4, 2021). *The U.S. Postal Inspection Service Looks Back at the 20th Anniversary of the Anthrax Mailings* https://www.uspis.gov/press-release-anthrax-mailing-20th-anniversary

Velikina, R., Dato, V., & Wagner, M. (2006). Governmental Public Health. In M. M. Wagner, A. W. Moore, & R. M. Aryel (Eds.), *Handbook of Biosurveillance* (pp. 67-196). Elsevier Academic Press. https://doi.org/https://doi.org/10.1016/B978-012369378-5/50000-4

Velsko, S., & Bates, T. (2016). A Conceptual Architecture for National Biosurveillance: Moving Beyond Situational Awareness to Enable Digital Detection of Emerging Threats. *Health Security*, *14*(3), 189-201. https://doi.org/10.1089/hs.2015.0063

Wagner, M. M. (2006a). Introduction. In M. M. Wagner, A. W. Moore, & R. M. Aryel (Eds.), *Handbook of Biosurveillance* (pp. 3-12). Elsevier Academic Press. https://doi.org/https://doi.org/10.1016/B978-012369378-5/50000-4

Wagner, M. M. (2006b). Methods of Evaluating Surveillance Data. In M. M. Wagner, A. W. Moore, & R. M. Aryel (Eds.), *Handbook of Biosurveillance* (pp. 313-319). Elsevier Academic Press. https://doi.org/https://doi.org/10.1016/B978-012369378-5/50000-4

Wagner, M. M., & Hogan, W. R. (2006). The Healthcare System. In M. M. Wagner, A. W. Moore, & R. M. Aryel (Eds.), *Handbook of Biosurveillance* (pp. 89-109). Elsevier Academic Press. https://doi.org/https://doi.org/10.1016/B978-012369378-5/50000-4

Wagner, M. M., Pavlin, J., Cox, K. L., & Cirino, N. M. (2006). Other Organizations That Conduct Biosurveillance. In M. M. Wagner, A. W. Moore, & R. M. Aryel (Eds.), *Handbook of Biosurveillance* (pp. 183-196). Elsevier Academic Press. https://doi.org/https://doi.org/10.1016/B978-012369378-5/50000-4

Woolston, C. (2021). *'Does anyone have any of these?': Lab-supply shortages strike amid global pandemic*. Nature. Retrieved September 27, 2022 from https://www.nature.com/articles/d41586-021-00613-y

World Health Organization. (2022a). *Coronavirus disease (COVID-19) pandemic*. World Health Organization. Retrieved September 14, 2022 from https://www.who.int/emergencies/diseases/novel-coronavirus-2019

World Health Organization. (2022b). *Joint external evaluation tool: international health regulations (2005)*. World Health Organization.

World Health Organization. (2022c). *One health*. World Health Organization. Retrieved September 21, 2022 from https://www.who.int/health-topics/one-health

World Health Organization, Food and Agriculture Organization, World Organisation for Animal Health, & Global Alliance for Rabies Control. (2018). *ZERO BY 30 The Global Strategic Plan to end human deaths from dog-mediated rabies by 2030*. World Health Organization, Food and Agriculture Organization of the United Nations, World Organisation for Animal Health, & Global Alliance for Rabies Control.

World Health Organization, Food and Agriculture Organization of the United Nations, World Organisation for Animal Health, & United Nations Environment Programme. (2022). *Strategic framework for collaboration on antimicrobial resistance - together for One health*. World Health Organization, Food and Agriculture Organization of the United Nations and World Organization for Animal Health.

World Health Organization, & United Nations Children's Fund. (2021). *Data for action: achieving high uptake of COVID-19 vaccines: gathering and using data on the behavioural and social drivers of vaccination: a guidebook for immunization programmes and implementing partners: interim guidance, 3 February 2021* CC BY-NC-SA 3.0 IGO). https://apps.who.int/iris/handle/10665/339452

World Organisation for Animal Health. (2019). *OIE tool for the evaluation of performance of veterinary services*. World Organisation for Animal Health.

World Organisation for Animal Health. (2020). *OIE Technical Factsheet: Infection with SARS-CoV-2 in Animals*. World Organisation for Animal Health. Retrieved October 19, 2022 from https://www.oie.int/fileadmin/Home/eng/Our_scientific_expertise/docs/pdf/COV-19/A_Factsheet_SARS-CoV-2.pdf

World Organisation for Animal Health. (2021). Animal Health Surveillance. In *Terrestrial Animal Health Code*. Paris, France: World Organisation for Animal Health.

World Organisation for Animal Health. (2022a). Glossary. In *Terrestrial Animal Health Code*. Paris, France: World Organisation for Animal Health.

World Organisation for Animal Health. (2022b). *One Health*. World Organisation for Animal Health. Retrieved September 14, 2022 from https://www.woah.org/en/what-we-do/global-initiatives/one-health/

Chapter 3

Air-sampling to detect animal and environmental bacteria at a cattle operation: pilot study for a potential novel method for animal health surveillance

3.1 Background

Zoonotic pathogens of livestock can cause foodborne diseases in humans, a major public health concern in the United States (U.S. Centers for Disease Control and Prevention, 2018). Enteric pathogens in farm animals also cause significant economic losses due to reduced weight gain, mortality, and treatment costs.

Current surveillance for enteric pathogens in food animals have mostly been limited to surveys conducted at slaughter plants or on farms. The testing for foodborne enteric pathogens at slaughter is at the end of the food animal production cycle and misses the opportunity for earlier intervention to reduce the microbial risk or burden. In addition, testing for foodborne enteric pathogens on farms requires increased movement of personnel and equipment onto the farm, increasing biosecurity risks. Due to the impact on public health and food animal production caused by the zoonotic enteric and environmental pathogens, conducting surveillance of this group of pathogens will allow additional and timely control measures to be taken to reduce the risk of foodborne disease.

The aerobiome is defined as microscopic organisms inhabiting the atmosphere, including viruses, bacteria, fungal spores, the DNA and RNA they contain, and range in size from nanometers to micrometers. Aerobiome composition changes in response to weather patterns, human activities and disturbances, and physical forces (Šantl-Temkiv et al., 2020). Air-sampling

for bioaerosols has been successfully used in studies on airborne transmission of infection, detection of infectious poultry diseases on a farm, and monitoring of airborne pathogens in hospitals (Ang et al., 2022; Brown et al., 2021; Hietala et al., 2005; Torremorell et al., 2016). However, the use of air-sampling as a surveillance tool for animal pathogens has been limited thus far. Air samples can be collected from outside the farm production area, and the potential benefits include improved animal welfare and improved biosecurity for the farm (Lago et al., 2018). This novel method for sample collection can potentially be used to enhance the data collection component of biosurveillance described in Chapter 2.

The objective of this study was to provide proof of concept on the potential of air-sampling as a method for surveillance of zoonotic and environmental pathogens in a livestock premises through a pilot study. My hypothesis is that air samples from a cattle operation will contain the same bacteria as cattle feces and soil from the same operation.

The samples collected from the farm were tested for four fecal or environmental bacteria. Firstly, *Escherichia coli* has an expected prevalence of 1.3 – 10.2 % in cattle (Omisakin et al., 2003; Sargeant et al., 2003). Some strains such as Enterohaemorrhagic *E. coli* (EHEC) colonize the colon of cattle, are shed in feces, and can contaminate food sources. Enterotoxigenic *E. coli* (ETEC) cause diarrhea in cattle, leading to production losses (Berry & Wells, 2010; McDonough et al., 2000). Secondly, *Salmonella* (non-typhoidal species) have an expected prevalence of 9 – 10 % in cattle and are a major cause of foodborne illness in the U.S. with cattle being common reservoirs. They can also cause diarrhea and production losses in cattle (Callaway et al., 2005; Gutema et al., 2019; Xie et al., 2016). Thirdly, *Bacillus cereus* is a spore-forming bacterium that can survive pasteurization and is a potential foodborne pathogen in milk. They are found in soil and feces

and can contaminate the teats of cattle prior to milking (Magnusson et al., 2007; Wu et al., 2007). Lastly, *Pseudomonas aeruginosa* is a bacterium that is commonly found in soil and water. They are opportunistic pathogens that can cause infections in cattle (e.g., mastitis), other animals, and humans (Moroni et al., 2018; Park et al., 2014).

3.2 Materials and methods

3.2.1 Location

Samples were collected from the outdoor cattle pens at the Colorado State University Agricultural Research, Development and Education Center (ARDEC) in Fort Collins, Colorado, United States on August 2, 2022. There were 115 head of beef cattle, comprising a mixture of Angus, Akaushi, Black Wagyu, and Hereford breeds. The cattle were between thirteen to seventeen months of age, housed in the cattle pens on the day of sampling. The cattle did not receive any veterinary treatment during the two weeks prior to sampling.

3.2.2 Weather conditions and farm activities

Weather conditions including cloud cover, temperature, humidity, wind speed and direction were recorded hourly during sample collection. Weather data was obtained from the National Weather Service for current conditions recorded at the Northern Colorado Regional Airport located 14 miles south of ARDEC (National Weather Service, 2022). Farm activities including the movement of cattle, personnel, and vehicles were observed and recorded.

3.2.3 Sample collection

Pooled fecal and soil samples were collected from the pens occupied by cattle. For the pooled fecal sample, approximately four grams of cattle feces was collected using a clean plastic

spoon from ten different locations within the pens and pooled in a clean plastic bag. For the pooled soil sample, soil at ten different locations within the pens near sources of moisture such as water troughs or puddles were loosened using a three-inch cutting sample ring (Figure 3.1). Approximately four grams of soil was collected using a clean plastic spoon from each location within the pens and pooled in a clean plastic bag.

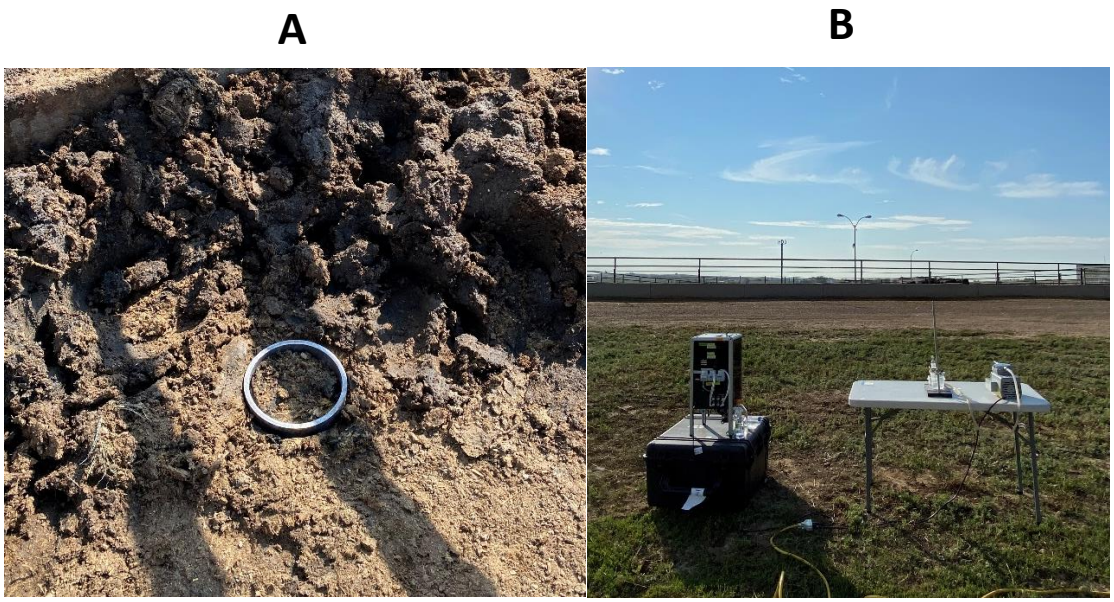


Figure 3.1. (A) Collection of soil sample using a three-inch cutting sample ring; (B) BioSampler and BioSpot 300p Bioaerosol Sampler at the downwind sampling location southeast of the cattle pens.

Air samples were collected northwest (predominant upwind) and southeast (predominant downwind) of the cattle pens (Figure 3.2), using both a BioSampler 20ml (SKC Inc.) and BioSpot 300p Bioaerosol Sampler[1] (Aerosol Devices inc.) at each location, for a continuous duration of four hours (0800-1200 hrs). The air-samplers were positioned approximately fifteen

[1] The BioSpot 300p Bioaerosol Sampler has been superseded by a newer model, BioSpot-VIVAS, which uses a similar laminar-flow water condensation broth tube method for collecting bioaerosols.

meters from the fence of the cattle pens (Figure 3.1). The height of the inlet of the BioSampler and BioSpot 300p devices were at approximately 1 and 1.1 meter respectively. The BioSampler devices operated at a flow rate of 12.5 L/min and the samples were collected in 20 ml sterile phosphate buffered saline (PBS). The BioSpot 300p devices operated at a flow rate of 8 L/min and the samples were collected in 2 ml sterile PBS. The conditions of the condensation growth tube in the BioSpot 300p were set to 8 °C (conditioner); 43 °C (initiator); 15 °C (moderator); 28 °C (nozzle); 20 °C (sample). The volumes of the samples were checked at one-hour intervals and refilled with sterile deionized water as needed to maintain constant volumes. The air-sampling equipment and collection methods have been described to be effective at maintaining the viability of microorganisms sampled from the air (Chang & Hung, 2012; Kesavan et al., 2010; Lin et al., 2000; Pan et al., 2018).

Figure 3.2. Layout of cattle pens and locations for fecal (FS), soil (FS), upwind (U) and downwind (D) air sample collection (Map sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community).

After sample collection, the fecal, soil, and air samples were stored on ice and transported to the laboratory within four hours.

3.2.4 Laboratory processing and analyses of samples

Sample processing and analyses were conducted in a biosafety level 2 laboratory. Refer to Appendix A for diagrams on the workflow of sample processing and bacterial culture and identification. The pooled fecal and soil samples were weighed and homogenized with an equal volume of sterile PBS. Ten grams of homogenized fecal and soil suspensions were further diluted 1 in 10 with sterile PBS. The air samples were centrifuged (Allegra X-12R Centrifuge, Beckman Coulter Inc.) at 2,000 g for 10 minutes, the supernatant discarded, and the pellet resuspended in 1 ml sterile PBS.

For *E. coli* culture and identification, the International Organization for Standardization (2020) protocol was used. A loop of sample suspension or *E. coli* positive control was streaked onto tryptone bile X-glucuronide agar (TBX) and incubated at 37 °C for 18-24 hours. Two blue-green suspect colonies from each sample that grew on TBX were sub-cultured onto a plate each of 5% sheep blood agar (SBA) and MacConkey agar (MCA) and incubated at 37 °C for 18-24 hours. Isolates which appeared grey on SBA and rose-red on MCA were identified and confirmed using Gram stain and the API 20 E test (bioMérieux Inc.).

For *Salmonella* spp. culture and identification, a protocol adapted from the National Veterinary Services Laboratories (2021) was used. Ten grams of homogenized fecal and soil suspensions were added to 100 ml of tetrathionate broth (TET). One hundred µl of each air sample suspension or a loop of *S. enterica* Typhimurium positive control were added to 5 ml of TET with three replicates each. The enrichment cultures were incubated at 37 °C in a shaking

incubator at 200 rpm for 18-24 hours. Thereafter, a loop of each TET enrichment culture was streaked onto xylose-lysine-tergitol-4 agar (XLT-4) and incubated at 37 °C for 18-24 hours. One yellow colony with a black center from each sample that grew on XLT-4 was sub-cultured onto a plate of 5% SBA and incubated at 37 °C for 18-24 hours. Isolates which grew on SBA were identified and confirmed using Gram stain and the API 20 E test (bioMérieux Inc.).

For *B. cereus* culture and identification, a protocol adapted from Stabb et al. (1994) was used. A loop of sample suspension or *B. cereus* UW85 positive control was streaked onto 0.1X trypticase soy agar (TSA) supplemented with polymyxin (25 µg/ml), cycloheximide (50 µg/ml), and ampicillin (50 µg/ml), and incubated at 28 °C for 1-3 days. Two flat, broad, and cream-colored colonies from each sample that grew on TSA were sub-cultured onto a plate of 5% SBA and incubated at 28 °C for 1-3 days. Isolates which grew on SBA were identified and confirmed by the presence of hemolysis on SBA and Gram stain.

For *P. aeruginosa* culture and identification, a protocol from Becton Dickinson GmbH (2013) was used. A loop of sample suspension or *P. aeruginosa* MPA01 positive control was streaked onto cetrimide agar (CET) and incubated at 37 °C for 18-24 hours. Isolates which grew on CET were identified and confirmed by the presence of yellow-green pigmentation of colonies, fluorescence under short wavelength (254nm) ultraviolet light, and Gram stain.

For non-selective bacterial culture, 100 µl of each air sample suspension that had been stored at 4 °C for two days were added to 5 ml 0.1X tryptic soy broth (TSB) with three replicates each. One hundred µl of sterile deionized water was used as negative control. The cultures were incubated at 28 °C in a shaking incubator at 200 rpm. After 24 and 48 hours, a loop of each TSB

culture was Gram stained and cultured for *E. coli*, *Salmonella* spp., *B. cereus*, and *P. aeruginosa* following the protocols described above.

3.3 Results

Based on hourly updates from the National Weather Service on weather conditions during the four-hour sampling period, cloud cover ranged from fair to partly cloudy, temperature ranged from 65 – 87 °F, humidity ranged from 32 – 68 %, wind speed ranged from 5 – 10 mph, and wind direction was predominately northwest. However, local wind directions at the farm location changed between northwest, north, southeast, and south. In terms of cattle activity, most animals were observed to be standing, lying down, or feeding at the troughs. A total of 42 cattle were walked out to the pasture for grazing and returned. Two people involved in the field study entered the cattle pens to collect fecal and soil samples, and a utility vehicle was observed driving across the farm four times. Otherwise, there was minimal human activity as the feed truck had topped up the feeding troughs before sampling commenced.

E. coli and *Salmonella* spp. were isolated from the pooled fecal sample. *E. coli* was isolated from the pooled soil sample. *B. cereus* and *P. aeruginosa* were not isolated from the pooled fecal and soil samples (Table 3.1).

E. coli, *Salmonella* spp., *B. cereus*, and *P. aeruginosa* were not isolated from the upwind and downwind air samples collected from both the BioSampler and BioSpot 300p Bioaerosol Sampler. Non-selective culture and Gram staining of all four air-samples detected a mixture of Gram-positive and Gram-negative bacilli and cocci (Table 3.1).

Table 3.1. Summary of bacterial culture and identification results.

		Test results				
		Non-specific culture	***E. coli***	***Salmonella* spp.**	***B. cereus***	***P. aeruginosa***
Sample types	**Feces**	NA	Detected	Detected	Not detected	Not detected
	Soil	NA	Detected	Not detected	Not detected	Not detected
	Upwind (BioSpot)	Gram positive & negative bacilli	Not detected	Not detected	Not detected	Not detected
	Downwind (BioSpot)	Gram positive & negative bacilli, gram positive cocci	Not detected	Not detected	Not detected	Not detected
	Upwind (BioSampler)	Gram positive & negative bacilli, gram positive cocci	Not detected	Not detected	Not detected	Not detected
	Downwind (BioSampler)	Gram positive & negative bacilli	Not detected	Not detected	Not detected	Not detected
	Positive controls	NA	Detected	Detected	Detected	Detected

3.4 Discussion

Contrary to their expected high prevalence in cattle feces or soil, *B. cereus* and *P. aeruginosa* were not detected in the fecal and soil samples collected from the cattle pens. This could be due to these two bacteria being absent in the cattle pen environment, or the hot and

dry weather conditions before the day of sampling being unfavorable for the survival of these bacteria in the environment. As *B. cereus* and *P. aeruginosa* were not detected in the cattle pen environment, their non-detection in the upwind and downwind air samples were not unexpected. As it is relatively easy to collect fecal and soil samples compared to air samples, in future studies the presence of the selected bacteria in soil and cattle feces from the study location should be confirmed before proceeding to collect the full set of samples.

The detection of *E. coli* and *Salmonella* spp. in fecal and soil samples were expected as both bacteria are known to colonize the gut of cattle and are shed in feces. The BioSampler and BioSpot 300p Bioaerosol Sampler were able to detect a mixture of Gram-positive and Gram-negative bacteria in both the upwind and downwind locations, however *E. coli* and *Salmonella* spp. were not detected. One possible reason is that even though *E. coli* and *Salmonella* spp. were present in the cattle pen environment, there were insufficient physical forces or environmental disturbances to loft the bacteria into the air during the time of air-sampling. This is consistent with the relatively low wind speeds and lack of human and animal activities observed during air-sampling. A second possible reason is that the air-sampling, processing, and laboratory analyses methods had insufficient sensitivity to detect *E. coli* and *Salmonella* spp. in the air. Firstly, even though the BioSampler and BioSpot 300p Bioaerosol Sampler were reported to be effective at maintaining the viability of microorganisms sampled in controlled environments, our study collected air samples at a continuous duration of four hours in an outdoor environment where the samples were physically agitated by air streams, exposed to evaporative loss, temperature fluctuation, and ultraviolet radiation, which could reduce the viability of bacteria. Secondly, both the BioSampler and BioSpot 300p Bioaerosol Sampler have relatively low flowrates of 12.5 L/min

and 8 L/min. These flowrates were designed to mimic the ventilation rate of human breathing and are useful in studies investigating human exposure to bioaerosols but may not be sensitive enough for the purpose of our pilot study which is to detect the presence or absence of microorganisms in the air. Finally, the bacterial culture protocols used in this study may not be able to detect the presence of bacteria below a certain minimum detection limit, or the bacteria sampled may be physiologically stressed from the sampling methods used and hence exhibit poor viability.

In terms of practicality, the BioSampler and BioSpot 300p Bioaerosol Sampler may not be ideal for collecting air-samples in a farm environment. The BioSampler is made of glass and the BioSpot 300p Bioaerosol Sampler has a water condensation growth tube, and both are susceptible to physical damage if they were dropped or toppled over. Both devices also require an external power source to run and power cords had to be extended over long distances to the sampling locations.

Several modifications are suggested to improve on this study's design. Firstly, more frequent sampling intervals for a longer period of time (e.g., two-hour samples over a twenty-four-hour period) will minimize environmental stressors on the collected samples. The higher time resolution would also allow samples collected to be more representative of changing weather conditions, human activities, and animal activities on the farm, and correspond to specific weather events or human activities, such as a strong gust of wind blowing from a specific direction. For example, collecting air samples during feeding time will coincide with high human and animal activity which may produce more physical forces to loft environmental bacteria into the air.

Air-samplers with higher flowrates could be used to sample a larger volume of air in shorter sampling intervals. It may not be necessary to use an air-sampler that uses impingement or water condensation methods to maintain the viability of bacteria collected. Several studies have demonstrated that impaction directly onto agar or filtration through gelatin filters were also suitable methods for isolating viable bacteria from the air (Chinivasagam et al., 2009; Cogliati et al., 2022; Pletinckx et al., 2011).

Air-samplers with built-in batteries could be used as this is more convenient than extending power cords over long distances and allows more flexibility in choosing sampling locations.

Molecular methods for detecting bacteria could be used to complement culture-based methods. Sample processing and culture methods for detecting bacteria may have limited sensitivity and may introduce ecological bias in the results depending on the sample media, culture media and incubation parameters used. Peccia and Hernandez (2006) described the benefits of incorporating polymerase chain reaction-based methods in the study of bioaerosols. These include increased sensitivity for detecting low biomass concentrations in air samples, decreased ecological biases, and the ability to quantify microorganisms in the air.

In conclusion, based on the results of this pilot study, air-sampling has not been shown to be an effective or practical method for the surveillance of animal and environmental bacteria on a cattle operation. However, due to the large number of variables in studying the aerobiome and limitations of this study, I believe that air-sampling can be an effective method of animal health surveillance with refinements to the air-sampling and sample analysis protocols.

3.5 References

Ang, A. X. Y., Luhung, I., Ahidjo, B. A., Drautz-Moses, D. I., Tambyah, P. A., Mok, C. K., Lau, K. J. X., Tham, S. M., Chu, J. J. H., Allen, D. M., & Schuster, S. C. (2022). Airborne SARS-CoV-2 surveillance in hospital environment using high-flowrate air samplers and its comparison to surface sampling. *Indoor air*, *32*(1), e12930-n/a. https://doi.org/10.1111/ina.12930

Becton Dickinson GmbH. (2013). BD Pseudosel Agar (Cetrimide Agar). In *Instructions for Use - Ready-to-use Plated Media* (Vol. PA-254419.06): Becton Dickinson GmbH.

Berry, E. D., & Wells, J. E. (2010). *Escherichia coli* O157:H7: Recent Advances in Research on Occurrence, Transmission, and Control in Cattle and the Production Environment. In S. L. Taylor (Ed.), *Advances in Food and Nutrition Research* (Vol. 60, pp. 67-118). Academic Press.

Brown, E., Nelson, N., Gubbins, S., & Colenutt, C. (2021). Environmental and air sampling are efficient methods for the detection and quantification of foot-and-mouth disease virus. *Journal of Virological Methods*, *287*, 113988. https://doi.org/https://doi.org/10.1016/j.jviromet.2020.113988

Callaway, T. R., Keen, J. E., Edrington, T. S., Baumgard, L. H., Spicer, L., Fonda, E. S., Griswold, K. E., Overton, T. R., VanAmburgh, M. E., Anderson, R. C., Genovese, K. J., Poole, T. L., Harvey, R. B., & Nisbet, D. J. (2005). Fecal Prevalence and Diversity of *Salmonella* Species in Lactating Dairy Cattle in Four States*. *Journal of Dairy Science*, *88*(10), 3603-3608. https://doi.org/https://doi.org/10.3168/jds.S0022-0302(05)73045-9

Chang, C.-W., & Hung, P.-Y. (2012). Evaluation of sampling techniques for detection and quantification of airborne legionellae at biological aeration basins and shower rooms. *Journal of aerosol science*, *48*, 63-74. https://doi.org/10.1016/j.jaerosci.2012.02.003

Chinivasagam, H. N., Tran, T., Maddock, L., Gale, A., & Blackall, P. J. (2009). Mechanically Ventilated Broiler Sheds: a Possible Source of Aerosolized *Salmonella*, *Campylobacter*, and *Escherichia coli*. *Applied and environmental microbiology*, *75*(23), 7417-7425. https://doi.org/10.1128/AEM.01380-09

Cogliati, M. G., Paez, P. A., Pianciola, L. A., Caputo, M. A., & Mut, P. N. (2022). Bioaerosol Concentration in a Cattle Feedlot in Neuquén, Argentina. *Atmosphere*, *13*(11), 1761. https://doi.org/10.3390/atmos13111761

Gutema, F. D., Agga, G. E., Abdi, R. D., De Zutter, L., Duchateau, L., & Gabriël, S. (2019). Prevalence and Serotype Diversity of *Salmonella* in Apparently Healthy Cattle: Systematic Review and Meta-Analysis of Published Studies, 2000-2017. *Frontiers in Veterinary Science*, *6*, 102-102. https://doi.org/10.3389/fvets.2019.00102

Hietala, S. K., Hullinger, P. J., Crossley, B. M., Kinde, H., & Ardans, A. A. (2005). Environmental air sampling to detect exotic Newcastle disease virus in two California commercial poultry flocks. *Journal of veterinary diagnostic investigation*, *17*(2), 198-200. https://doi.org/10.1177/104063870501700219

International Organization for Standardization. (2020). Microbiology of the food chain — Horizontal method for the enumeration of beta-glucuronidase-positive *Escherichia coli* — Part 3: Detection and most probable number technique using 5-bromo-4-chloro-3-indolyl-ß-D-glucuronide (ISO Standard No. 16649-3:2015). In *07.100.30 Food microbiology*: International Organization for Standardization.

Kesavan, J., Schepers, D., & McFarland, A. R. (2010). Sampling and Retention Efficiencies of Batch-Type Liquid-Based Bioaerosol Samplers. *Aerosol science and technology*, *44*(10), 817-829. https://doi.org/10.1080/02786826.2010.497513

Lago, A. P., Lorenzo, G. L., Fernández, P. D., Cao, J. M. D., Baños, P. D., & Rodríguez, G. F. (2018). Viral and Bacterial Environmental Detection in Livestock Farms. In *Reference Module in Earth Systems and Environmental Sciences*. Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-409548-9.11252-7

Lin, X., Reponen, T., Willeke, K., Wang, Z., Grinshpun, S. A., & Trunov, M. (2000). Survival of Airborne Microorganisms During Swirling Aerosol Collection. *Aerosol science and technology*, *32*(3), 184-196. https://doi.org/10.1080/027868200303722

Magnusson, M., Christiansson, A., & Svensson, B. (2007). *Bacillus cereus* spores during housing of dairy cows: factors affecting contamination of raw milk. *J Dairy Sci*, *90*(6), 2745-2754. https://doi.org/10.3168/jds.2006-754

McDonough, P. L., Rossiter, C. A., Rebhun, R. B., Stehman, S. M., Lein, D. H., & Shin, S. J. (2000). Prevalence of *Escherichia coli* O157:H7 from cull dairy cows in New York State and comparison of culture methods used during preharvest food safety investigations. *Journal of Clinical Microbiology*, *38*(1), 318-322. https://doi.org/10.1128/JCM.38.1.318-322.2000

Moroni, P., Nydam, D. V., Ospina, P. A., Scillieri-Smith, J. C., Virkler, P. D., Watters, R. D., Welcome, F. L., Zurakowski, M. J., Ducharme, N. G., & Yeager, A. E. (2018). 8 - Diseases of the Teats and Udder. In S. F. Peek & T. J. Divers (Eds.), *Rebhun's Diseases of Dairy Cattle (Third Edition)* (pp. 389-465). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-323-39055-2.00008-5

National Veterinary Services Laboratories. (2021). Isolation of *Salmonella* from Reptile and Environmental Samples (NVSL-SOP-0193). In *Laboratory Activities*: United States Department of Agriculture.

National Weather Service. (2022). *Current conditions at Fort Collins/Loveland - Northern Colorado Regional Airport (KFNL)*. Retrieved August 2, 2022 from https://forecast.weather.gov/MapClick.php?x=146&y=59&site=bou&zmx=&zmy=&map_x=146&map_y=59#.Y4E7zHbMKUk

Omisakin, F., MacRae, M., Ogden, I. D., & Strachan, N. J. C. (2003). Concentration and prevalence of *Escherichia coli* O157 in cattle feces at slaughter. *Applied and environmental microbiology*, *69*(5), 2444-2447. https://doi.org/10.1128/AEM.69.5.2444-2447.2003

Pan, M., Carol, L., Lednicky, J. A., Eiguren-Fernandez, A., Hering, S., Fan, Z. H., & Wu, C.-Y. (2018). Collection of airborne bacteria and yeast through water-based condensational growth. *Aerobiologia*, *34*(3), 337-348. https://doi.org/10.1007/s10453-018-9517-7

Park, H. R., Hong, M. K., Hwang, S. Y., Park, Y. K., Kwon, K. H., Yoon, J. W., Shin, S., Kim, J. H., & Park, Y. H. (2014). Characterisation of *Pseudomonas aeruginosa* related to bovine mastitis. *Acta Vet Hung*, *62*(1), 1-12. https://doi.org/10.1556/AVet.2013.054

Peccia, J., & Hernandez, M. (2006). Incorporating polymerase chain reaction-based identification, population characterization, and quantification of microorganisms into aerosol science: A review. *Atmospheric environment (1994)*, *40*(21), 3941-3961. https://doi.org/10.1016/j.atmosenv.2006.02.029

Pletinckx, L. J., Verhegghe, M., Dewulf, J., Crombé, F., De Bleecker, Y., Rasschaert, G., Goddeeris, B. M., & De Man, I. (2011). Screening of poultry-pig farms for methicillin-resistant

Staphylococcus aureus: Sampling methodology and within herd prevalence in broiler flocks and pigs. *Infection, genetics and evolution*, *11*(8), 2133-2137. https://doi.org/10.1016/j.meegid.2011.07.008

Šantl-Temkiv, T., Sikoparija, B., Maki, T., Carotenuto, F., Amato, P., Yao, M., Morris, C. E., Schnell, R., Jaenicke, R., Pöhlker, C., DeMott, P. J., Hill, T. C. J., & Huffman, J. A. (2020). Bioaerosol field measurements: Challenges and perspectives in outdoor studies. *Aerosol science and technology*, *54*(5), 520-546. https://doi.org/10.1080/02786826.2019.1676395

Sargeant, J. M., Sanderson, M. W., Smith, R. A., & Griffin, D. D. (2003). *Escherichia coli* O157 in feedlot cattle feces and water in four major feeder-cattle states in the USA. *Prev Vet Med*, *61*(2), 127-135. https://doi.org/10.1016/s0167-5877(03)00166-1

Stabb, E. V., Jacobson, L. M., & Handelsman, J. (1994). Zwittermicin A-producing strains of *Bacillus cereus* from diverse soils. *Applied and environmental microbiology*, *60*(12), 4404-4412. https://doi.org/10.1128/aem.60.12.4404-4412.1994

Torremorell, M., Alonso, C., Davies, P. R., Raynor, P. C., Patnayak, D., Torchetti, M., & McCluskey, B. (2016). Investigation into the Airborne Dissemination of H5N2 Highly Pathogenic Avian Influenza Virus During the 2015 Spring Outbreaks in the Midwestern United States. *Avian Diseases*, *60*(3), 637-643. https://doi.org/10.1637/11395-021816-Reg.1

U.S. Centers for Disease Control and Prevention. (2018). *Estimates of Foodborne Illness in the United States*. Retrieved November 27, 2022 from https://www.cdc.gov/foodborneburden/2011-foodborne-estimates.html

Wu, X. Y., Walker, M., Vanselow, B., Chao, R. L., & Chin, J. (2007). Characterization of mesophilic bacilli in faeces of feedlot cattle. *J Appl Microbiol*, *102*(3), 872-879. https://doi.org/10.1111/j.1365-2672.2006.03106.x

Xie, Y., Savell, J. W., Arnold, A. N., Gehring, K. B., Gill, J. J., & Taylor, T. M. (2016). Prevalence and Characterization of *Salmonella enterica* and *Salmonella* Bacteriophages Recovered from Beef Cattle Feedlots in South Texas. *Journal of Food Protection*, *79*(8), 1332-1340. https://doi.org/10.4315/0362-028X.JFP-15-526

Chapter 4

Behavioral barriers, enablers, and interventions for animal disease reporting: scoping review and mapping to behavioral frameworks

4.1 Background

Animal disease reporting by animal owners and producers involves the reporting of clinical or subclinical suspect cases to the veterinary authorities. In most countries, there are legal obligations for veterinarians, animal owners, and producers to report suspected cases of notifiable animal diseases to the veterinary authority. It is an important component of passive surveillance to quickly detect cases of animal disease in a population so that actions can be taken to contain and eradicate the disease before it spreads (Salman, 2003). However, animal diseases remain underreported, and some commonly cited reasons include the lack of awareness and knowledge of reportable diseases by the stakeholders, and the lack of appropriate compensation (Elbers et al., 2010; Zepeda & Salman, 2003).

Even though animal disease reporting by animal producers and owners is an important component of animal health surveillance, there has been limited research on barriers and enablers that influence reporting, and the effectiveness of interventions to improve reporting. In a systematic review on social research data collection methods used to investigate animal disease reporting behavior, Enticott et al. (2021) recommended more studies on animal disease reporting to include behavioral mechanisms to improve the understanding of how disease reporting works. A scoping review by Gates et al. (2021) provided a good overview of factors that influenced

animal disease reporting behavior in farmers, but did not attempt to explain those factors in terms of behavioral theories.

Behavioral theories provide an explanation of the structural and psychological mechanisms believed to control behavior and changes in behavior (Atkins et al., 2017). Behavior change frameworks, such as the Theoretical Domains Framework (TDF), are a synthesis of multiple theories and were initially developed to investigate the influences on public health behavior, such as factors that encourage physical activity and interventions to reduce smoking (Atkins et al., 2017). They have since been used in different sectors and are relevant to study the factors that lead to underreporting of animal diseases and interventions to improve reporting. More recently, Michie et al. (2014) developed the Behavior Change Wheel (BCW) to help non-behavioral science specialists design interventions for behavior change. The BCW is a synthesis of 19 frameworks of behavior change and recognizes that behavior is influenced by capability, opportunity, and motivation (collectively known as the COM-B model).

A scoping review is a method of literature review to synthesize evidence to address a broad research question (Arksey & O'Malley, 2005). The aim of this study is to conduct a scoping review to identify behavioral barriers, enablers, and interventions for animal owners and producers reporting animal diseases to veterinary authorities. The barriers, enablers, and interventions will then be mapped to behavioral frameworks to understand the mechanisms of action that influence disease reporting so that a broader range of interventions guided by theory and evidence can be considered.

4.2 Methods

4.2.1 Pilot and full study

This study is a collaboration between the author and experts from the United States Department of Agriculture (USDA), Animal and Plant Health Inspection Service (APHIS), Center for Epidemiology and Animal Health (CEAH), and USDA, National Agricultural Library (NAL). The study is ongoing at the time of preparing this thesis, hence this report will focus on a pilot conducted to test and refine the scoping review protocol that will be used to conduct the full scoping review.

4.2.2 Scoping review

Scoping reviews are a rigorous and transparent method of evidence synthesis to address broad and exploratory research questions, such as identifying key characteristics or factors related to a concept (Morris et al., 2016; Munn et al., 2018; Peters et al., 2020). Scoping reviews allow for a comprehensive search for evidence as both published and unpublished (gray literature) primary sources of evidence can be considered (Peters et al., 2020). Thus, we chose a scoping review in this study as our objectives were to explore, summarize, and map evidence on animal disease reporting behavior.

We developed a protocol that aligned with the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) statement (Tricco et al., 2018).

4.2.3 Research question and definitions

We formulated the research question for the scoping review using the PICO (Population, Intervention, Comparator, and Outcome) framework (Table 4.1) which facilitated the subsequent literature search and screening criteria (Fineout-Overholt & Johnston, 2005; Peters et al., 2020). We defined the question to be addressed by the scoping review as: what are the behavioral barriers, enablers, and interventions for animal owners and producers reporting animal diseases to veterinary authorities?

Table 4.1. Formulation of research question using the PICO (population, intervention, comparator, and outcome) framework.

Key elements	Definition	Components in this study
Population	Population demographics, characteristics, and other qualifying criteria.	Animal owners and producers.
Intervention	Interventions being considered.	Behavioral barriers, enablers, and interventions.
Comparator	Comparison of intervention with a control.	Not applicable.
Outcomes	Desired effects of the intervention.	Animal disease reporting.

To ensure congruent and uniform understanding of the scope of the research question by reviewers and readers, we defined each component in the PICO framework for this study (Table 4.2).

Table 4.2. Definitions of each component in the research question.

Components in this study	Definition
Animal owners and producers	All stakeholders that are responsible for animals under their care. Animals include any terrestrial or aquatic animals, companion animals, livestock, zoo animals, wildlife, and bees.

	Examples include pet owners, pet breeders, livestock farmers, livestock smallholders, animal caretakers, zoo animal keepers, veterinarians, game officers, game managers, game wardens, wildlife managers, hunters.
Behavioral barriers and enablers	Factors that negatively or positively influence behavior. Behavior refers to anything a person (both individual or collective) does in response to internal or external events. Actions may be overt and directly measurable, or covert and indirectly measurable; behaviors are physical events that occur in the body and are controlled by the brain (American Psychological Association, 2023; Michie et al., 2014).
Behavioral interventions	An activity or coordinated set of activities that aims to get an individual or population to behave differently from how they would have acted without such an action (Michie et al., 2014).
Animal disease reporting	Animal owners and producers report suspected cases of reportable animal diseases to a veterinary authority. Reportable animal diseases refer to animal diseases specified by veterinary authorities, and that, as soon as detected or suspected, should be brought to the attention of the authority, in accordance with national regulations (World Organisation for Animal Health, 2022).

4.2.4 Eligibility criteria

This scoping review will include articles on behavioral barriers, enablers, and interventions for animal owners and producers reporting animal diseases to veterinary authorities. In the pilot, less stringent inclusion criteria were used, and several issues were encountered. The reviewers discussed the issues and refined the inclusion criteria that will be used for the full study (Table 4.3).

Table 4.3. Eligibility criteria used in the pilot and issues encountered.

Characteristics of sources of evidence	Initial eligibility criteria	Revised eligibility criteria
Types of articles	We will include articles published in a peer-reviewed journal or gray literature authored by an international or governmental organization. Commentaries, opinion pieces, and conference abstracts will be excluded as they are unlikely to provide sufficient details or primary information on animal disease reporting behavior. <u>Issues encountered</u> The research findings in academic theses and dissertations may be subsequently published in peer-reviewed journals which may cause duplication of evidence. Theses and dissertations also tend to be lengthy and are resource intensive to conduct full-text screening.	We will include articles published in a peer-reviewed journal or gray literature authored by an international or governmental organization. Commentaries, opinion pieces, and conference abstracts will be excluded as they are unlikely to provide sufficient details or primary information on animal disease reporting behavior. Academic theses and dissertations will be excluded as significant research findings are likely to be published in peer-reviewed journals subsequently.
Date range	We will include articles published between January 1924 (the year WOAH and international standards of animal disease reporting was established) and the date the search was conducted. <u>Issues encountered</u> Nil.	We will include articles published between January 1924 (the year WOAH and international standards of animal disease reporting was established) and the date the search was conducted.
Language	The search will be open to all languages. If the number of non-English articles is equal to or less than 20, title and abstract will be google translated and included if meets inclusion criteria. <u>Issues encountered</u> Even though it may be feasible to translate article titles and abstracts	We will consider only English language articles.

	that are relatively short, the translation of full texts with sufficient accuracy to evaluate the eligibility criteria is not feasible.	
Population	We will include animal owners and producers, with no restriction on geographical region. <u>Issues encountered</u> Nil.	We will include animal owners and producers, with no restriction on geographical region.
Interventions	We will include behavioral barriers, enablers, or interventions that are primary information, generated from evidence and not opinions, such as those obtained from interviews, surveys, focus groups, expert elicitations, observational studies, case studies, trials, etc. Behavioral barriers and enablers will be included if they are clear, precise, distinct, and observable. Behavioral interventions will be included if they are evaluated for effectiveness of the outcome within their respective studies. <u>Issues encountered</u> Some articles identified barriers that were associated with animal disease reporting rates but there was insufficient details or evidence to map them to components in behavioral frameworks. For example, small herd sizes were associated with lower rates of disease reporting (Bronner et al., 2015). Some authors suggested behavioral interventions to improve on animal disease reporting. However, interventions that are presented as suggestions lack details on proposed behavioral mechanisms	We will include behavioral barriers, enablers, or interventions that are primary information, generated from evidence and not opinions, such as those obtained from interviews, surveys, focus groups, expert elicitations, observational studies, case studies, trials, etc. Behavioral barriers and enablers will be included if they are clear, precise, distinct, and observable. Behavioral interventions will be included if they are evaluated for effectiveness of the outcome within their respective studies.

	of actions. For example, having a credible communicator was suggested as a solution to changing the attitudes and thinking of poultry farmers to reporting suspect cases of avian influenza (Elbers et al., 2010).	
Outcome	We will include animal disease reporting by animal owners and producers to veterinary authorities. <u>Issues encountered</u> Nil.	We will include animal disease reporting by animal owners and producers to veterinary authorities.

4.2.5 Information sources

In the pilot, a search for relevant articles was conducted on the Web of Science and Scopus databases by a librarian from the CEAH (USDA, APHIS).

For the full study, a more comprehensive literature search will be conducted by librarians from the NAL (USDA) on the following bibliographic databases: AGRICOLA, Aquatic Sciences and Fisheries Abstracts, CAB Abstracts, APA PsychInfo, PubMed, Web of Science, and Zoological Record. Gray literature articles will be searched on WOAH and World Health Organization (WHO) databases. Controlled vocabulary such as Medical Subject Headings (MeSH) and truncated search terms will be combined using Boolean and proximity operators to reach a balance between sensitivity and specificity when searching for articles. Snowballing strategy may be used to identify additional references from included studies and from published literature reviews (secondary information sources) that are relevant to the scope of the study.

4.2.6 Search strategy

The search strategy used in the pilot study is detailed in **Appendix B**. The search results were exported to EndNote (Clarivate Plc), and duplicates removed. The deduplicated search results were then then exported to Rayyan (Rayyan Systems Inc.) for screening. Critical appraisal and data charting were performed in forms on Microsoft Excel (Microsoft Corp.).

More comprehensive search strategies for the full study will be drafted by NAL (USDA) librarians and refined through team discussions. An example of a draft search strategy for PubMed can be found in **Appendix C**. Similar search terms with modifications to the syntax will be used for the other databases. The search results will be exported to EndNote, and duplicates removed. The deduplicated search results will then be exported to DistillerSR (DistillerSR Inc.) for screening, critical appraisal, and data charting. It is expected that the use of a systematic review software with more integrated and machine learning functions will increase the speed and reduce errors in conducting the scoping review.

4.2.7 Selection of sources of evidence

The pilot search produced 125 articles. A random sample of 25 articles were selected using random numbers generated in Microsoft Excel. A pilot test of the scoping review protocols was conducted where three independent reviewers screened the 25 articles. We discussed the results and refined the screening, critical appraisal, and data charting forms to prepare for the full scoping review.

For the full study, two independent reviewers will evaluate the titles and abstracts of articles identified in the searches to exclude articles that are not relevant to the study.

Disagreements will be resolved by discussion and consensus. Following this, two independent reviewers will evaluate the full text of articles to confirm the inclusion of articles that passed the title and abstract screening. Similarly, disagreements at this step will be resolved by discussion and consensus. The reviewers will explore the use and availability of artificial intelligence algorithms to facilitate or automate the literature screening process. The selection process will be recorded and the PRISMA flow diagram will be provided (Tricco et al., 2018).

4.2.8 Data charting process and data items

In the full study, data charting will be conducted independently by two reviewers on a form created in DistillerSR. The results will be discussed and continuously updated in an iterative process. The data extraction form will include variables listed in Table 4.4.

Table 4.4. Data charting variables.

Title
Authors
Year of publication
Peer-reviewed or gray literature
Country of study
Study objectives
Animal disease(s) specified
Whether diseases(s) specified are zoonotic
Behavioral barriers
Behavioral enablers
Behavioral interventions

4.2.9 Critical appraisal of sources of evidence

The quality of the articles will be appraised using criteria adapted from the Mixed Methods Appraisal Tool (MMAT) Version 2018 (Hong et al., 2018). Articles will be appraised on whether they have clear research questions and whether the data collected address the research

questions in the respective articles. Two reviewers will independently appraise the included articles. Disagreements will be resolved by discussion and consensus.

4.2.10 Data analysis and synthesis of results

Descriptive statistics will be used to describe the type of literature included, countries of study, the context of animal diseases, and whether they are zoonotic.

Behavioral barriers and enablers to animal disease reporting will be mapped to domains of the Theoretical Domains Framework (TDF) (Cane et al., 2012) and components of the COM-B model (Michie et al., 2014). Refer to **Appendix D and E** for details and definitions of the TDF and COM-B model respectively.

Behavioral interventions to animal disease reporting will be mapped to Behavior Change Techniques (BCT) of the Behavior Change Techniques Taxonomy version 1 (BCTTv1) (Michie et al., 2013) and intervention functions of the BCW (Michie et al., 2014). Refer **Appendix F and G** for details and definitions of the BCTTv1 and BCW intervention functions respectively.

We will analyze the behavioral barriers, enablers, and interventions that have been coded to the respective behavioral frameworks and present our findings on animal disease reporting from a socio-behavioral perspective. We will also discuss the implications on animal health surveillance and suggest potential strategies to improve animal disease reporting.

4.3 Results

4.3.1 Descriptive summary of included articles in the pilot

A total of 6 articles were included after the random sample of 25 articles were screened. A total of 13 articles were screened in full text, and 7 articles were excluded because they did not

fulfil the eligibility criteria (Figure 4.1). All 6 included articles were peer-reviewed journal articles and were appraised to have clear research questions with data collected to address their respective research questions.

Details of the included articles are summarized in **Appendix H**. The articles covered 11 countries distributed across 2 continents (Europe and Oceania). In terms of the disease reporting population, 5 articles covered animal producers, 1 covered animal hunters, and 1 covered veterinarians. In terms of animal disease context, 4 articles covered specific animal diseases, and of these 2 were zoonotic diseases. A total of 5 articles contained primary information on behavioral barriers, 5 articles contained primary information on behavioral enablers, and no articles contained primary information on behavioral interventions.

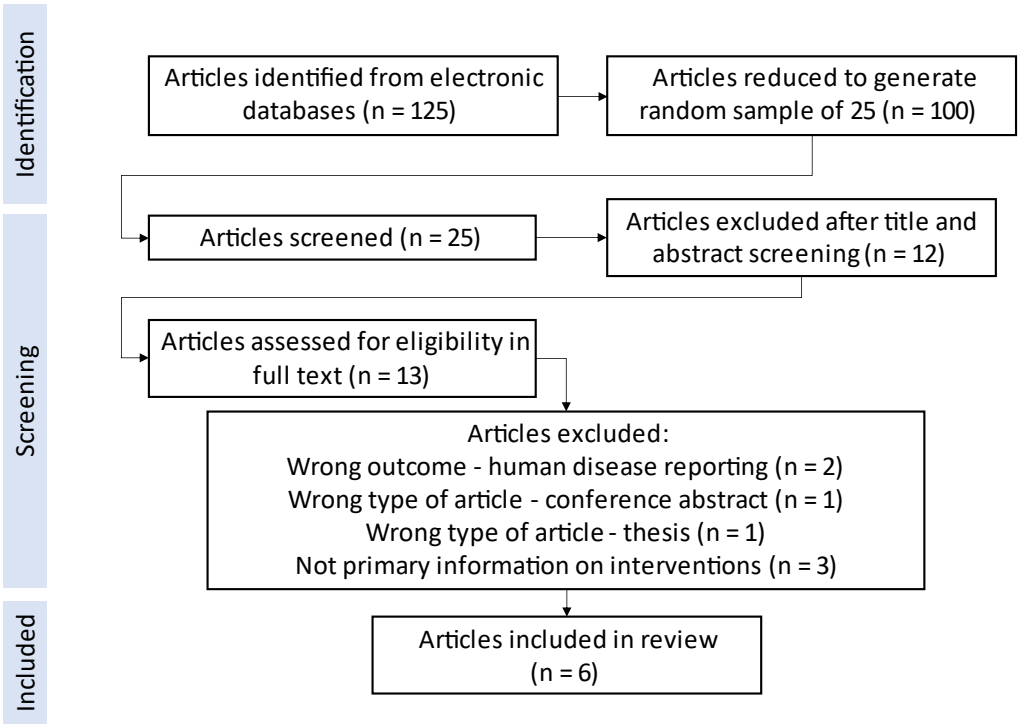


Figure 4.1. Flow diagram from bibliographic search of articles to final inclusion in the pilot review.

4.4 Discussion

4.4.1 Using behavioral frameworks to understand behavior and behavior change

The action of animal disease reporting by animal owners and producers is a desired outcome in this study. It is difficult to change behavior, such as increasing the rate of animal disease reporting, but the use of behavior change theories and evidence can increase the effectiveness of behavioral interventions (Cane et al., 2012). To effectively implement behavior change, we should understand the factors that influence the desired behavior and perform interventions that can positively alter those factors. Behavioral theories are used to understand the mechanisms behind barriers and enablers to disease reporting and guide the selection and implementation of interventions to change behavior.

There are many behavioral theories with overlapping ideas which make it challenging for practical use by implementors (Atkins et al., 2017). Hence, Michie et al. (2005) and Cane et al. (2012) developed and refined the Theoretical Domains Framework (TDF), which is a synthesis of 33 behavior and behavior change theories whose constructs are integrated and clustered into 14 domains which cover the cognitive, affective, social and environmental factors that influence behavior (refer to **Appendix D** for details). A simplified framework, the COM-B model, has 6 components that influence behavior (refer to **Appendix E** for details), and each of these components are linked to the TDF (Michie et al., 2014). The use of the simpler COM-B model increases the accessibility of behavioral frameworks to researchers who may not be experts in social and behavioral sciences but may not allow the granularity to differentiate influences on a particular behavior. For example, the COM-B model may not provide sufficient details on the influences of psychological capability and reflective motivation compared to the TDF (Atkins et

al., 2017). Nevertheless, when either the TDF or COM-B model is used for behavioral analysis, the domains or components that are identified to have a large influence on the desired behavior can be used to inform the types of interventions to change that behavior (Cane et al., 2012; Michie et al., 2014).

The behavior change technique taxonomy (BCTT) is a standardized language used in describing, analyzing, and implementing interventions, thus avoiding the uncertainty and confusion when different non-standardized labels are used. Behavior change interventions have different mechanisms of effecting change, known as behavior change techniques (BCT). A BCT is an observable, replicable, and irreducible component of a behavioral intervention to change causal processes that influence behavior (Michie et al., 2013). The BCTT is a standardized labelling of 93 distinct BCTs in 16 clusters developed by Michie et al. (2013) as the 'active ingredients' of behavior change interventions. The benefits of using the BCTT include allowing the accurate implementation of effective interventions, the accurate replication of interventions for comparative research, the reliable extraction of information on interventions for reviews, and a better understanding of mechanisms of action and intervention development (Michie et al., 2013). A simplified framework of BCTs, comprising 9 intervention functions in the Behavior Change Wheel (BCW), facilitates non-behavioral science specialists in designing interventions to change behavior (Michie et al., 2014).

In summary, the TDF and COM-B model are used to identify what factors need to change to achieve the desired behavior. The BCT and BCW intervention functions are used to determine what can be done to improve animal disease reporting. The identification of TDF domains or COM-B components influencing animal disease reporting, will inform the types of BCT or BCW

intervention functions that will likely be effective in bringing about the desired behavior change (Michie et al., 2014).

4.4.2 Demonstration of mapping behavioral barriers to interventions using behavioral frameworks

We present examples to demonstrate the mapping of evidence on behavioral barriers extracted from two articles using both the TDF (Table 4.5) and COM-B model (Table 4.6), linking them to BCT and BCW intervention functions that are likely to be effective to increase disease reporting behavior respectively. These links were identified by consensus exercise among groups of experts and should be thought of as options that can be applied as interventions. For example, Elbers et al. (2010) found that one barrier for disease reporting was that "farmers felt that during past animal disease eradication campaigns they were pushed aside and they were not in control of their business anymore". This negative interpersonal experience had affected the social opportunity (COM-B component) for disease reporting. Based on this, one possible environmental restructuring (intervention function) is that during eradication campaigns, the veterinary authorities designate relationship managers to farmers to receive their feedback and to provide updates on the operations.

Table 4.5. Mapping text on behavioral barriers to TDF and linking them to BCT.

Article	Text description of barrier	TDF domain	BCTs likely to be effective
(Elbers et al., 2010)	Farmers felt that during past animal disease eradication campaigns they were pushed aside and they were not in control of their business anymore.	Social influences	• Social comparison • Social support or encouragement (general) • Information about others' approval • Social support (emotional) • Social support (practical) • Vicarious reinforcement • Restructuring the social environment • Modelling or demonstrating the behavior • Identification of self as role model • Social reward
(Elbers et al., 2010)	In the layer sector in the Netherlands there is almost no regular veterinary supervision, and health problems are commonly discussed with technical / non veterinary advisers from poultry integrations or the feed industry.	Environmental context and resources	• Restructuring the physical environment • Discriminate (learned) cue • Prompts / cues • Restructuring the social environment • Avoidance / changing exposure to cues for the behavior
(Vergne et al., 2016)	Hunters indicating that they do not report the presence of wild boar carcasses frequently attributed this behavior to being unaware of the possibility to report.	Knowledge	• Health consequences • Biofeedback • Antecedents • Feedback on behavior

Table 4.6. Mapping text on behavioral barriers to COM-B model and linking them to BCW intervention functions.

Article	Text description of barrier	COM-B component	BCW intervention functions likely to be effective
(Elbers et al., 2010)	Farmers felt that during past animal disease eradication campaigns they were pushed aside and they were not in control of their business anymore.	Social opportunity	• Restriction • Environmental restructuring • Modelling • Enablement
(Elbers et al., 2010)	In the layer sector in the Netherlands there is almost no regular veterinary supervision, and health problems are commonly discussed with technical / non veterinary advisers from poultry integrations or the feed industry.	Physical opportunity	• Training • Restriction • Environmental restructuring • Enablement
(Vergne et al., 2016)	Hunters indicating that they do not report the presence of wild boar carcasses frequently attributed this behavior to being unaware of the possibility to report.	Psychological capability	• Education • Training • Environmental restructuring • Modelling • Enablement

It should be noted that although these suggested BCTs and BCW intervention functions do not to provide specific designs of behavior change interventions, they do provide a systematic and theoretically guided method for identifying the types of interventions that are expected to be effective for increasing animal disease reporting (behavior) by animal owners and producers (target population) (Michie et al., 2014). Specific intervention design will ultimately depend on the local context and circumstances (Cane et al., 2015; Michie et al., 2014).

4.4.3 Limitations of study

Firstly, the exclusion of articles in languages other than English may omit potential sources of evidence on animal disease reporting. Secondly, there may be difficulty mapping text on behavioral barriers, enablers, and interventions to labels of behavioral frameworks as articles may not provide sufficiently detailed descriptions. This is partially overcome by having two independent reviewers conducting the mapping. If there remains uncertainty on the mapping of text and consensus cannot be reached, the text is proposed to be excluded from mapping.

4.5 References

American Psychological Association. (2023). *APA Dictionary of Psychology*. Retrieved January 16, 2023 from https://dictionary.apa.org/behavior

Arksey, H., & O'Malley, L. (2005). Scoping studies: towards a methodological framework. *International journal of social research methodology*, *8*(1), 19-32. https://doi.org/10.1080/1364557032000119616

Atkins, L., Francis, J., Islam, R., O'Connor, D., Patey, A., Ivers, N., Foy, R., Duncan, E. M., Colquhoun, H., Grimshaw, J. M., Lawton, R., & Michie, S. (2017). A guide to using the Theoretical Domains Framework of behaviour change to investigate implementation problems. *Implementation science : IS*, *12*(1), 77-77. https://doi.org/10.1186/s13012-017-0605-9

Bronner, A., Morignat, E., & Calavas, D. (2015). Respective influence of veterinarians and local institutional stakeholders on the event-driven surveillance system for bovine brucellosis in France. *BMC Veterinary Research*, *11*(1), 179. https://doi.org/10.1186/s12917-015-0499-1

Cane, J., O'Connor, D., & Michie, S. (2012). Validation of the theoretical domains framework for use in behaviour change and implementation research. *Implementation science : IS*, *7*(1), 37-37. https://doi.org/10.1186/1748-5908-7-37

Cane, J., Richardson, M., Johnston, M., Ladha, R., & Michie, S. (2015). From lists of behaviour change techniques (BCTs) to structured hierarchies: Comparison of two methods of developing a hierarchy of BCTs. *British journal of health psychology*, *20*(1), 130-150. https://doi.org/10.1111/bjhp.12102

Elbers, A. R. W., Gorgievski-Duijvesteijn, M. J., Zarafshani, K., & Koch, G. (2010). To report or not to report: a psychosocial investigation aimed at improving early detection of avian influenza outbreaks. *Revue Scientifique Et Technique-Office International Des Epizooties*, *29*(3), 435-449. https://doi.org/10.20506/rst.29.3.1988

Enticott, G., Earl, L., & Gates, M. C. (2021). A systematic review of social research data collection methods used to investigate voluntary animal disease reporting behaviour. *Transboundary and Emerging Diseases*, *00*, 1-15. https://doi.org/10.1111/tbed.14407

Fineout-Overholt, E., & Johnston, L. (2005). Teaching EBP: Asking Searchable, Answerable Clinical Questions. *Worldviews on evidence-based nursing*, *2*(3), 157-160. https://doi.org/10.1111/j.1741-6787.2005.00032.x

Gates, M. C., Earl, L., & Enticott, G. (2021). Factors influencing the performance of voluntary farmer disease reporting in passive surveillance systems: A scoping review. *Preventive Veterinary Medicine*, *196*. https://doi.org/10.1016/j.prevetmed.2021.105487

Hong, Q., Pluye, P., Fàbregues, S., Bartlett, G., Boardman, F., Cargo, M., Dagenais, P., Gagnon, M.-P., Griffiths, F., Nicolau, B., O'Cathain, A., Rousseau, M.-C., & Vedel, I. (2018). *Mixed Methods Appraisal Tool (MMAT), version 2018*. Retrieved January 10, 2023 from http://mixedmethodsappraisaltoolpublic.pbworks.com/w/page/127425845/Download%20the%20MMAT

Michie, S., Atkins, L., & West, R. (2014). *The Behaviour Change Wheel: A Guide to Designing Interventions*. Silverback Publishing.

Michie, S., Johnston, M., Abraham, C., Lawton, R., Parker, D., & Walker, A. (2005). Making psychological theory useful for implementing evidence based practice: a consensus

approach. *Quality & safety in health care*, *14*(1), 26-33. https://doi.org/10.1136/qshc.2004.011155

Michie, S., Richardson, M., Johnston, M., Abraham, C., Francis, J., Hardeman, W., Eccles, M. P., Cane, J., & Wood, C. E. (2013). The Behavior Change Technique Taxonomy (v1) of 93 Hierarchically Clustered Techniques: Building an International Consensus for the Reporting of Behavior Change Interventions. *Annals of behavioral medicine*, *46*(1), 81-95. https://doi.org/10.1007/s12160-013-9486-6

Morris, M., Boruff, J. T., & Gore, G. C. (2016). Scoping reviews: establishing the role of the librarian. *Journal of the Medical Library Association*, *104*(4), 346-353. https://doi.org/10.3163/1536-5050.104.4.020

Munn, Z., Peters, M. D. J., Stern, C., Tufanaru, C., McArthur, A., & Aromataris, E. (2018). Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. *BMC medical research methodology*, *18*(1), 143-143. https://doi.org/10.1186/s12874-018-0611-x

Peters, M., Godfrey, C., McInerney, P., Munn, Z., Tricco, A., & Khalil, H. (2020). Scoping Reviews. In E. Aromataris & Z. Munn (Eds.), *JBI Manual for Evidence Synthesis*. JBI. https://doi.org/https://doi.org/10.46658/JBIMES-20-12

Salman, M. D. (2003). Surveillance and Monitoring Systems for Animal Health Programs and Disease Surveys. In M. D. Salman (Ed.), *Animal disease surveillance and survey systems : methods and applications* (1st ed., pp. 3-13). Iowa State Press. https://doi.org/10.1002/9780470344866

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M. D. J., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C., . . . Straus, S. E. (2018). PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. *Annals of internal medicine*, *169*(7), 467-473. https://doi.org/10.7326/M18-0850

Vergne, T., Guinat, C., Petkova, P., Gogin, A., Kolbasov, D., Blome, S., Molia, S., Pinto Ferreira, J., Wieland, B., Nathues, H., & Pfeiffer, D. U. (2016). Attitudes and Beliefs of Pig Farmers and Wild Boar Hunters Towards Reporting of African Swine Fever in Bulgaria, Germany and the Western Part of the Russian Federation. *Transboundary and Emerging Diseases*, *63*(2), e194-e204. https://doi.org/10.1111/tbed.12254

World Organisation for Animal Health. (2022). Glossary. In *Terrestrial Animal Health Code*. Paris, France: World Organisation for Animal Health.

Zepeda, C., & Salman, M. D. (2003). Planning Survey, Surveillance, and Monitoring Systems - Roles and Requirements. In M. D. Salman (Ed.), *Animal disease surveillance and survey systems : methods and applications* (1st ed., pp. 35-46). Iowa State Press. https://doi.org/10.1002/9780470344866

Chapter 5

Application of a biosurveillance system: a theoretical demonstration using leptospirosis

5.1 Introduction

The previous chapters in this thesis have provided an overview of the animal health components in a biosurveillance system and potential areas of enhancements to the role of animal health in biosurveillance. In this final chapter, I will demonstrate the application of these principles and components in a theoretical model using leptospirosis to highlight the strengths, limitations, and practical considerations in designing and implementing a biosurveillance system.

5.2 Leptospirosis

Leptospirosis is a zoonotic disease caused by several serovars of *Leptospira* bacteria and is prevalent in many countries. This disease affects a wide range of hosts, including humans, companion animals, livestock, wildlife, and rodent pests. Infections in animals may be subclinical or present with fever, renal damage, hepatic damage, and abortions in pregnant animals. In humans, infections may asymptomatic or cause fever, muscle aches, vomiting, jaundice, and may be fatal in some cases. Leptospirosis may be treated with antibiotics and vaccines are available for dogs, horses, cattle, and pigs (Dirsmith et al., 2013; Duncan et al., 2012; Lunn, 2022; U.S. Centers for Disease Control and Prevention, 2019; World Organisation for Animal Health, 2021).

Animals are the maintenance hosts for specific *Leptospira* serovars (Table 5.1) and are reservoirs of infection for humans and other animals. Humans are incidental hosts and become infected through occupational (e.g., veterinary staff, dairy workers) or recreational (e.g.,

swimming in contaminated waters) exposure (Lunn, 2022; U.S. Centers for Disease Control and Prevention, 2019).

Table 5.1. Common maintenance hosts of pathogenic *Leptospira (Lunn, 2022)*.

***Leptospira* serovars**	**Maintenance hosts**
Bratislava	Pigs
Canicola	Dogs
Grippotyphosa	Raccoons Muskrats Skunks Voles
Hardjo	Cattle
Icterohaemorrhagiae	Rats
Pomona	Cattle Pigs Opossums Skunks

Transmission of *Leptospira* may occur directly through contact with infected urine, placental fluids, or milk. Indirect transmission may occur through contact with contaminated water and soil (Figure 5.1) (Adler, 2015; Adler & Peña Moctezuma, 2010; Lunn, 2022). The involvement of humans, animals, and the environment in the transmission of leptospirosis makes this an ideal example to demonstrate a biosurveillance system.

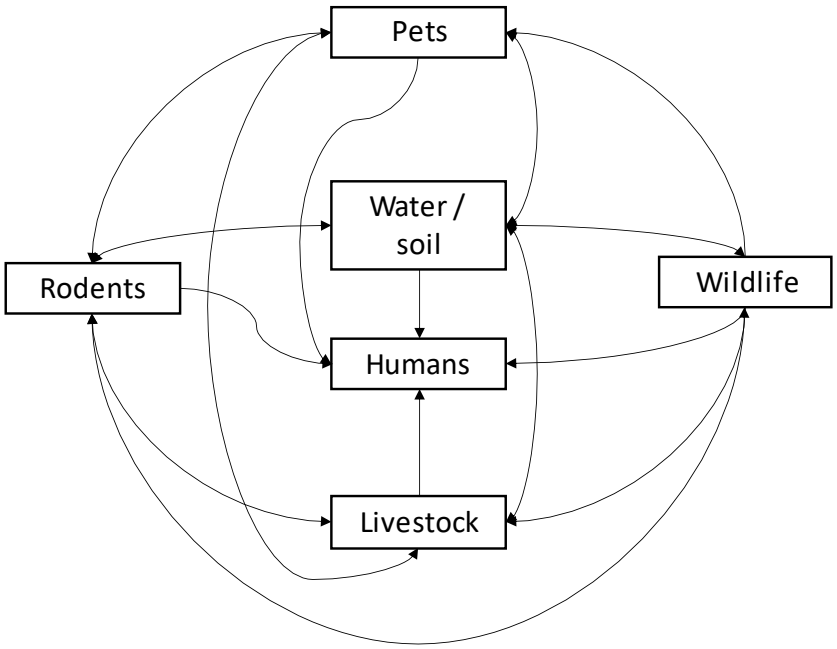


Figure 5.1. Transmission cycle of leptospirosis.

5.3 Basic surveillance system for leptospirosis

In this example, we demonstrate a hypothetical basic structure of a surveillance system in a country endemic for leptospirosis (Figure 5.2). In this general structure, data are collected from stakeholders, analyzed, and used by decision-makers to direct some forms of action in response to the health event. Surveillance data on leptospirosis in humans and animals are obtained from compulsory and voluntary disease reporting of confirmed cases respectively. When such reports are received, public and animal health authorities may decide to conduct disease investigation and implement control measures to manage the cases. Educational interventions may also be taken to increase awareness on the disease among stakeholders. This system allows for case detection and determining the frequency of leptospirosis in humans so that control measures can be taken.

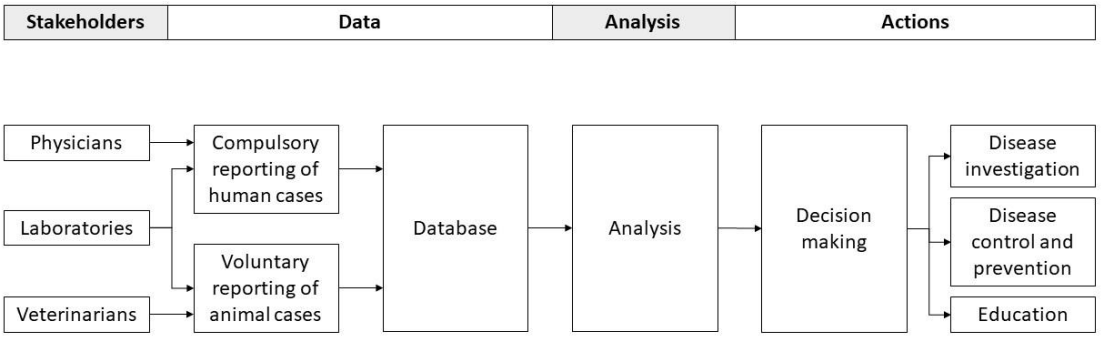


Figure 5.2. Hypothetical basic surveillance system for leptospirosis in an endemic country.

There are several limitations in this hypothetical surveillance system. Firstly, detecting cases or determining the frequency of leptospirosis in animals may not be effective as voluntary reporting is likely to result in underreporting of cases. This has a negative influence on animal health since control measures may not be implemented in response to cases. More importantly, this has negative influence on public health since cases of leptospirosis in animals is a risk factor for transmission to humans. Secondly, this surveillance system neither achieves early warning nor contributes to overall situational awareness of leptospirosis in the population. Since data are only collected on confirmed cases, the types of actions are limited to reactionary measures to investigate and control outbreaks. There is limited data available for analysis to support preemptive actions to reduce the risk of leptospirosis prior to potential outbreaks.

5.4 Enhanced biosurveillance system for leptospirosis

In this next example, we demonstrate a hypothetical enhanced structure of a biosurveillance system in a country endemic for leptospirosis (Figure 5.3). The green boxes illustrate the additional data streams, stakeholders, and actions in this enhanced biosurveillance

system. This example is not an exhaustive list of components for an ideal biosurveillance system but serves to demonstrate additive enhancements over Figure 5.2.

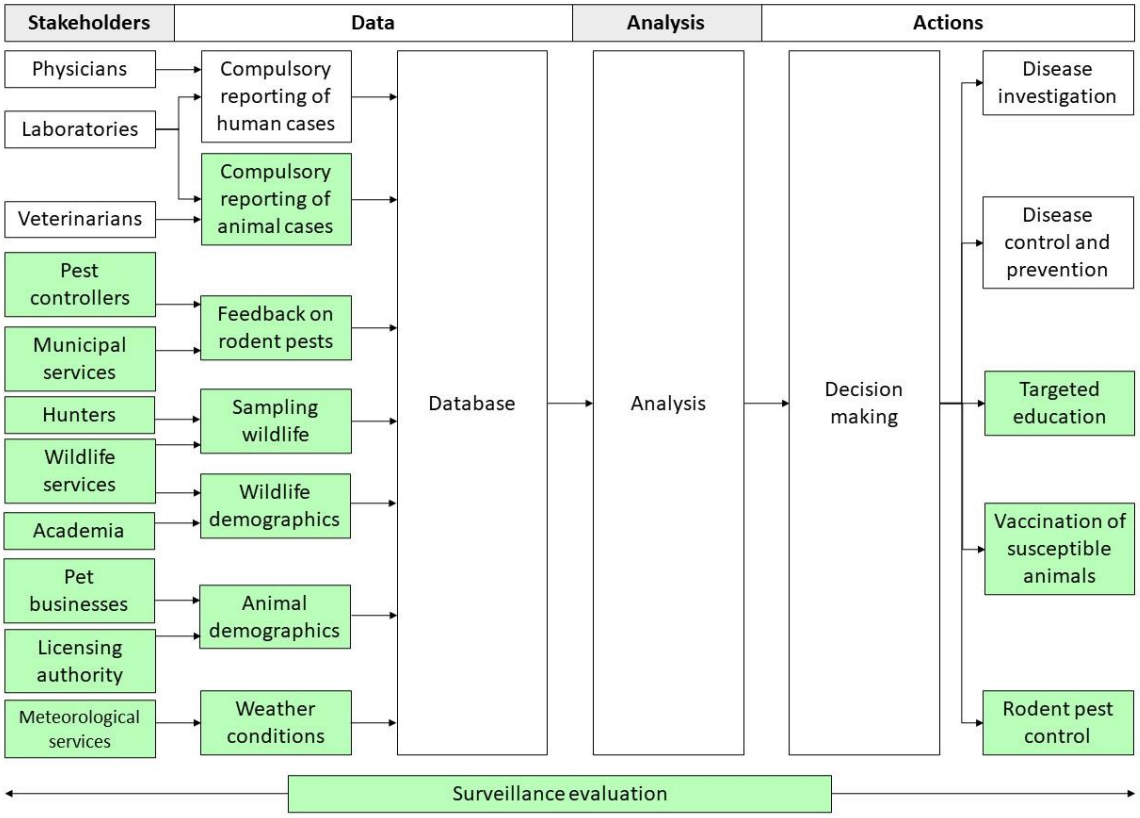


Figure 5.3. Hypothetical enhanced biosurveillance system for leptospirosis in an endemic country.

Compulsory reporting of leptospirosis cases in animals will increase the sensitivity of detecting cases and allow disease investigation and control measures to be implemented to reduce the risk of transmission to other animals and humans. However, to effectively implement this new data stream, policy changes (chapter 2.3.3) are required to support additional financial resources and legal powers for the animal health authorities. In addition, behavior-change interventions (chapters 2.3.4 and 4) are needed to encourage disease reporting by veterinarians.

These may include intervention functions such as education, training, incentivization, and rules. Other additional data streams on demographics and environmental data on pest rodents and weather conditions contribute to biosurveillance for leptospirosis and similar policy support and behavior interventions are required to implement these new data streams.

Demographic data on animals and wildlife provide baseline data (e.g., population size) to determine epidemiological indices and may contain population characteristics that increase their risk of leptospirosis exposure. Increased pest rodent population and warm wet weather conditions are associated with increased risk for leptospirosis transmission (Costa et al., 2022; Griffiths et al., 2022; Lunn, 2022; Ward, 2002). The number of complaints to municipal services on rodent infestations and weather data from local meteorological stations may be used to monitor these risk factors respectively. Hence, the continuous or regular data collection on pest rodent population density and weather conditions are syndromic data streams that can provide earlier signals of potential outbreaks, allowing preemptive actions to be taken before an outbreak occurs (chapter 2.3.5). However, the increased volume and variability of data mean that enhancements are required to data stream integration, processing, analysis, and decision-making (chapter 2.3.6). For example, data formats will require standardization and data will need to be shared across agencies and stakeholders. In terms of analysis, time-series and spatial analysis methods may be used to identify patterns and trends in the transmission of leptospirosis (Costa et al., 2022; Dhewantara et al., 2019). Predictive models and machine learning algorithms may be used to predict leptospirosis outbreaks based on multiple variables such as meteorological data, allowing disease prevention programs to be implemented (Ahangarcani et al., 2019; Desvars et al., 2011; Jayaramu et al., 2023). If we can predict the timing and location of future

outbreaks, interventions such as education on risk-reduction behaviors, vaccination of susceptible animals, and pest rodent control may be targeted at higher risk locations and populations, allowing more efficient and effective use of resources.

This enhanced biosurveillance system is an improvement to the basic surveillance system as it allows for early warning and contributes to overall situational awareness of leptospirosis in the population. Additional data streams from different One Health sectors may be added to this structure to improve information generated for decision-making, such as the proximity of livestock premises to residential areas, the amount of human-wildlife interaction, and local soil type. However, this will increase the complexity and cost of the system. Biosurveillance systems need to be sustainable and withstand external challenges while being effective at achieving their objectives. Hence, surveillance evaluation (chapter 2.3.7) should be performed regularly to ensure that the biosurveillance system remains effective and efficient at achieving its objectives, and modifications can be made to ensure continued relevance.

5.5 Discussion

The theoretical demonstration of a biosurveillance system for leptospirosis provides a practical illustration on how biosurveillance can be used to improve our understanding of disease threats and actions to safeguard public and animal health with One Health collaboration.

The strengths of a biosurveillance system include the integration of multiple data sources, hence providing a comprehensive view of disease occurrences and threats. The use of advanced data analysis methods allow the detection of patterns and trends that may not be immediately obvious. This ability to provide early warning and situational awareness will enable the relevant

authorities and stakeholders to respond more quickly and support the development of more effective disease control and prevention strategies.

Biosurveillance systems may have potential limitations. Firstly, the development and implementation of a biosurveillance system can be expensive and complex, requiring significant technical and financial resources. Secondly, a wide range of data are required for collection and analysis, but the availability and quality of data may vary in different locations and over time. Nevertheless, these limitations may be overcome by enhancements to the various components in a biosurveillance system discussed in this thesis.

5.6 Conclusion

Several areas of research are recommended to enhance biosurveillance. Firstly, the development of new technologies and tools, such as autonomous collection and multiplex testing of environmental samples will improve the speed and accuracy of disease detection. Secondly, understanding human behavior is essential for effective disease surveillance and control. Behavioral science research can help to understand the underlying mechanisms of action that influence disease surveillance and control behavior by stakeholders and determine behavioral intervention strategies that are effective at improving biosurveillance. Finally, advancements in artificial intelligence and machine learning techniques can enhance data collection, integration, analysis, and decision making in biosurveillance systems. In conclusion, biosurveillance systems are important in addressing the current and future health challenges facing our world. The continued efforts of the global health community and the support of animal health and veterinary professions to biosurveillance are needed to provide early detection and rapid response to

emerging health threats. This requires a collaborative effort from all One Health sectors and a sustained commitment to promoting health, sustainability, and wellbeing for all.

5.7 References

Adler, B. (2015). *Leptospira and leptospirosis*. Springer. https://doi.org/10.1007/978-3-662-45059-8

Adler, B., & Peña Moctezuma, A. (2010). Leptospira and leptospirosis. *Veterinary Microbiology*, *140*(3), 287-296. https://doi.org/https://doi.org/10.1016/j.vetmic.2009.03.012

Ahangarcani, M., Farnaghi, M., Shirzadi, M. R., Pilesjö, P., & Mansourian, A. (2019). Predictive risk mapping of human leptospirosis using support vector machine classification and multilayer perceptron neural network. *Geospatial Health*, *14*(1), 53. https://doi.org/10.4081/gh.2019.711

Costa, A. C. T. R. B., Pereira, C. R., Sáfadi, T., Heinemann, M. B., & Dorneles, E. M. S. (2022). Climate influence the human leptospirosis cases in Brazil, 2007-2019: a time series analysis. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, *116*(2), 124-132. https://doi.org/10.1093/trstmh/trab092

Desvars, A., Jego, S., Chiroleu, F., Bourhy, P., Cardinale, E., & Michault, A. (2011). Seasonality of Human Leptospirosis in Reunion Island (Indian Ocean) and Its Association with Meteorological Data. *PLOS ONE*, *6*(5), e20377-e20377. https://doi.org/10.1371/journal.pone.0020377

Dhewantara, P. W., Lau, C. L., Allan, K. J., Hu, W., Zhang, W., Mamun, A. A., & Soares Magalhães, R. J. (2019). Spatial epidemiological approaches to inform leptospirosis surveillance and control: A systematic review and critical appraisal of methods. *Zoonoses and public health*, *66*(2), 185-206. https://doi.org/10.1111/zph.12549

Dirsmith, K., VanDalen, K., Fry, T., Charles, B., VerCauteren, K., & Duncan, C. (2013). Leptospirosis in Fox Squirrels (Sciurus niger) of Larimer County, Colorado, USA. *Journal of wildlife diseases*, *49*(3), 641-645. https://doi.org/10.7589/2012-10-265

Duncan, C., Krafsur, G., Podell, B., Baeten, L. A., LeVan, I., Charles, B., & Ehrhart, E. J. (2012). Leptospirosis and Tularaemia in Raccoons (Procyon lotor) of Larimer Country, Colorado: Leptospirosis and Tularaemia in Raccoons of Colorado. *Zoonoses and public health*, *59*(1), 29-34. https://doi.org/10.1111/j.1863-2378.2011.01412.x

Griffiths, J., Yeo, H. L., Yap, G., Mailepessov, D., Johansson, P., Low, H. T., Siew, C.-C., Lam, P., & Ng, L. C. (2022). Survey of rodent-borne pathogens in Singapore reveals the circulation of Leptospira spp., Seoul hantavirus, and Rickettsia typhi. *Scientific Reports*, *12*(1), 2692-2692. https://doi.org/10.1038/s41598-021-03954-w

Jayaramu, V., Zulkafli, Z., De Stercke, S., Buytaert, W., Rahmat, F., Abdul Rahman, R. Z., Ishak, A. J., Tahir, W., Ab Rahman, J., & Mohd Fuzi, N. M. H. (2023). Leptospirosis modelling using hydrometeorological indices and random forest machine learning. *International journal of biometeorology*. https://doi.org/10.1007/s00484-022-02422-y

Lunn, K. F. (2022). *Leptospirosis in Animals - Overview*. Retrieved February 12, 2023 from https://www.merckvetmanual.com/generalized-conditions/leptospirosis/leptospirosis-in-animals-overview

U.S. Centers for Disease Control and Prevention. (2019). *Leptospirosis*. U.S. Centers for Disease Control and Prevention. Retrieved February 12, 2023 from https://www.cdc.gov/leptospirosis/

Ward, M. P. (2002). Seasonality of canine leptospirosis in the United States and Canada and its association with rainfall. *Preventive Veterinary Medicine*, *56*(3), 203-213. https://doi.org/10.1016/S0167-5877(02)00183-6

World Organisation for Animal Health. (2021). Manual of Diagnostic Tests and Vaccines for Terrestrial Animals. In *Leptospirosis*: World Organisation for Animal Health.

Chapter 6

Future directions: what is needed?

Emerging and endemic disease agents constantly threaten the health of people, animals, and the ecosystem. Biosurveillance and One Health collaboration are required to achieve early detection and warning, contribute to overall situational awareness of the health aspects of an incident, and to enable better decision making at all levels to develop holistic solutions and utilize the full spectrum of disease control to contribute to global health.

The animal health community has a major role in biosurveillance. National animal health authorities should take lead in enhancing the animal health components in biosurveillance. An important first step is reviewing existing animal health surveillance systems to enhance data streams, data integration, and analysis for decision-making. This will require more effective engagement of stakeholders and collaboration between different agencies and stakeholders in the One Health sectors. In reality, this is a complex task and would likely require small steps and an iterative process to achieve gradual and continuous refinement to the biosurveillance system. At the same time, when faced with ever changing external challenges and limited resources, surveillance evaluation is an important tool to ensure biosurveillance systems remain relevant, effective, and efficient in achieving their objectives.

In our interconnected world where diseases do not respect borders, research on enhancing biosurveillance and success stories on implementation should be shared widely. This will inspire greater engagement, support, and collective effort for biosurveillance to safeguard the health and well-being of all people, animals, and the environment.

Appendix A

Diagrams on the workflow of sample processing and bacterial culture and identification

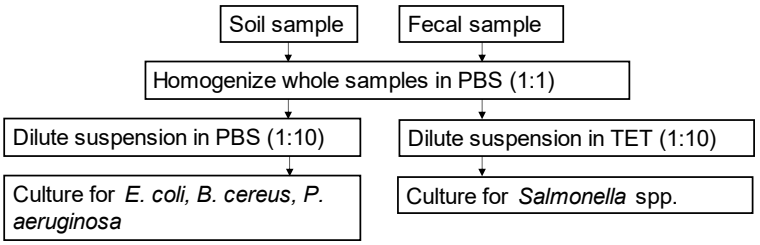


Figure A1. Workflow of sample processing for pooled fecal and soil samples.

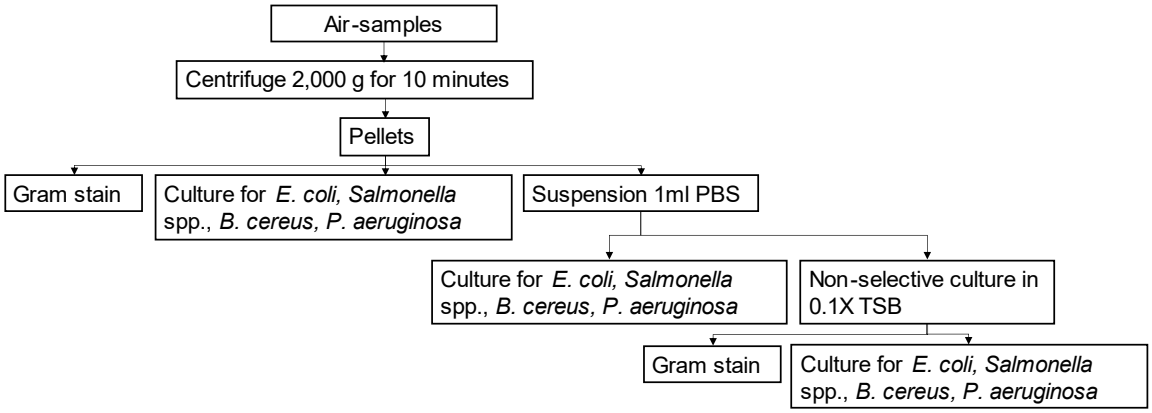


Figure A2. Workflow of sample processing for air samples.

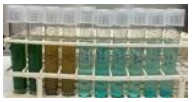
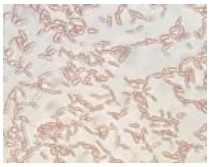
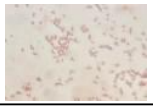
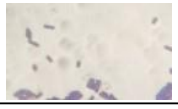
E. coli	Salmonella spp.	B. cereus	P. aeruginosa
1. Tryptone Bile X-glucuronide Agar (TBX) 	1. TET enrichment 	1. 0.1X Trypticase Soy Agar (TSA) + polymyxin (25µg/ml), cycloheximide (50µg/ml), ampicillin (50µg/ml) 	1. Cetrimide Agar  
2. 5% Sheep Blood Agar (SBA) and MacConkey Agar (MCA) 	2. Xylose-lysine-tergitol-4 agar (XLT -4) 	2. 5% SBA 	2. Gram staining 
3. Gram staining & API 20E  	3. Gram staining & API 20E  	3. Gram staining 	

Figure A3. Workflow of bacterial culture and identification for *E. coli*, *Salmonella* spp., *B. cereus*, and *P. aeruginosa*.

Appendix B

Search strategy for databases in the pilot

Table B1. Web of Science search strategy (performed on January 24, 2022).

Searches conducted	Search terms
Search 1	"disease reporting" (all fields) and behavior (all fields)
Search 2	"disease reporting (all fields) and (socio* or social*) (all fields)

Table B2. Scopus search strategy (performed on January 24, 2022).

Searches conducted	Search terms
Search 3	(TITLE-ABS-KEY (("disease report*" OR surveillance)) AND TITLE-ABS-KEY ((livestock OR cattle OR sheep OR goat OR swine OR pig*)) AND TITLE-ABS-KEY ((socio* OR social OR behavior* OR behaviour* OR attitude* OR perception* OR vigil* OR barrier* OR "participatory epidemiology")))
Search 4	(TITLE-ABS-KEY ((disease AND reporting)) AND TITLE-ABS-KEY ((decision OR "decision process" OR "decision making" OR attitude OR perception)) AND TITLE-ABS-KEY ((detection OR surveillance)))

Appendix C

Draft search strategy for PubMed database in the full study

Table C1. Draft PubMed search strategy including the use of controlled vocabulary, Medical Subject Headings (MeSH), and proximity operators.

Key elements	Components in this study	Search terms
Population	Animal owners and producers	farmer*[Title/Abstract] OR producer*[Title/Abstract] OR "farm manager*"[Title/Abstract] OR " farm operator*"[Title/Abstract] OR "livestock manager*"[Title/Abstract] OR "agricultural worker*"[Title/Abstract] OR ("animal owner"[Title/Abstract: ~3] OR "animal owners"[Title/Abstract:~3] OR "animals owner"[Title/Abstract:~3] OR "animals owners"[Title/Abstract:~3]) OR ("pet owner"[Title/Abstract:~3] OR "pet owners"[Title/Abstract:~3] OR "pets owner"[Title/Abstract:~3] OR "pets owners"[Title/Abstract:~3]) OR "pet parent*"[Title/Abstract] OR breeder*[Title/Abstract] OR "owned animal*"[Title/Abstract] OR ("animal keeper"[Title/Abstract:~3] OR "animal keepers"[Title/Abstract:~3] OR "animals keeper"[Title/Abstract:~3] OR "animals keepers"[Title/Abstract:~3]) OR "zoo keeper*"[Title/Abstract] OR zookeeper*[Title/Abstract] OR ("livestock keeper"[Title/Abstract:~3] OR "livestock keepers"[Title/Abstract:~3]) OR veterinarian*[Title/Abstract] OR "vet tech*"[Title/Abstract] OR technician*[Title/Abstract] OR ("animal caretaker"[Title/Abstract:~3] OR "animal caretakers"[Title/Abstract:~3] OR "animals caretaker"[Title/Abstract:~3] OR "animals caretakers"[Title/Abstract:~3]) OR "animal care staff"[Title/Abstract] OR hobbyist*[Title/Abstract] OR "livestock smallholder*"[Title/Abstract] OR "animal smallholder*"[Title/Abstract] OR ("animal trainer"[Title/Abstract:~3] OR "animal trainers"[Title/Abstract:~3] OR "animals trainer"[Title/Abstract:~3] OR "animals trainers"[Title/Abstract:~3]) OR ("livestock trainer"[Title/Abstract:~3] OR "livestock trainers"[Title/Abstract:~3]) OR jockey*[Title/Abstract] OR "racing association"[Title/Abstract] OR "track management"[Title/Abstract] OR grooms[Title/Abstract] OR "racing authorit*"[Title/Abstract] OR cowhand*[Title/Abstract] OR cowherd*[Title/Abstract] OR cowboy*[Title/Abstract] OR rancher*[Title/Abstract] OR "ranch worker*"[Title/Abstract] OR herdsmen[Title/Abstract] OR herder*[Title/Abstract] OR shepherd*[Title/Abstract] OR aquaculturist*[Title/Abstract] OR beekeeper*[Title/Abstract] OR apiculturist*[Title/Abstract] OR biologist*[Title/Abstract] OR

		"environmental scientist*"[Title/Abstract] OR gamekeeper*[Title/Abstract] OR "game keeper*"[Title/Abstract] OR "game warden*"[Title/Abstract] OR ranger*[Title/Abstract] OR "rehabilitator*"[Title/Abstract] OR "animal shelter*"[Title/Abstract] OR zoologist*[Title/Abstract] OR hunter*[Title/Abstract] OR "control operator*"[Title/Abstract] OR officer*[Title/Abstract] OR "Farmers"[Mesh] OR "Veterinarians"[Mesh] OR "Animal Technicians"[Mesh] OR "Laboratory Personnel"[Mesh]
Intervention	Behavioral barriers, enablers, and interventions	psycholog*[Title/Abstract] OR "acceptance"[Title/Abstract] OR "access"[Title/Abstract] OR "accountability"[Title/Abstract] OR adaptability[Title/Abstract] OR "adopt*"[Title/Abstract] OR "administrate"[Title/Abstract] OR "administrative"[Title/Abstract] OR "altruism"[Title/Abstract] OR "assistance"[Title/Abstract] OR attitude*[Title/Abstract] OR "avoidance"[Title/Abstract] OR barrier*[Title/Abstract] OR "approach Behavior"[Title/Abstract] OR "planned behavior"[Title/Abstract] OR "reporting behavior*"[Title/Abstract] OR "approach Behaviour"[Title/Abstract] OR "planned behaviour"[Title/Abstract] OR "reporting behaviour*"[Title/Abstract] OR "discrete choice"[Title/Abstract:~3] OR "behavior choice"[Title/Abstract:~3] OR "behaviour choice"[Title/Abstract:~3] OR "discrete choices"[Title/Abstract:~3] OR "behavior choices"[Title/Abstract:~3] OR "behaviour choices"[Title/Abstract:~3] OR belief*[Title/Abstract] OR "blame"[Title/Abstract] OR budget*[Title/Abstract] OR "capacity"[Title/Abstract] OR "choice"[Title/Abstract] OR "cognitive"[Title/Abstract] OR "collaborat*"[Title/Abstract] OR "complexity"[Title/Abstract] OR "compliance"[Title/Abstract] OR "cooperation"[Title/Abstract] OR "co-operation"[Title/Abstract] OR "cost benefit"[Title/Abstract] OR "credibility"[Title/Abstract] OR "cues"[Title/Abstract] OR "curiosity"[Title/Abstract] OR "decision report"[Title/Abstract:~3] OR "decisions report"[Title/Abstract:~3] OR "decision reporting"[Title/Abstract:~3] OR "decisions reporting"[Title/Abstract:~3] OR "make decision"[Title/Abstract:~3] OR "make decisions"[Title/Abstract:~3] OR "making decision"[Title/Abstract:~3] OR "making decisions"[Title/Abstract:~3] OR "made decision"[Title/Abstract:~3] OR "made decisions"[Title/Abstract:~3] OR "maker decision"[Title/Abstract:~3] OR "maker decisions"[Title/Abstract:~3] OR "decided"[Title/Abstract] OR "economics"[Title/Abstract] OR "emotional"[Title/Abstract] OR "emotions"[Title/Abstract] OR facilitat*[Title/Abstract] OR fear*[Title/Abstract] OR "framing effect*"[Title/Abstract] OR habit[Title/Abstract] OR habits[Title/Abstract] OR "help-seeking"[Title/Abstract] OR "incentives"[Title/Abstract] OR "incentivize"[Title/Abstract] OR indeterminac*[Title/Abstract] OR "inexperienced"[Title/Abstract] OR "information seeking"[Title/Abstract] OR instinct*[Title/Abstract] OR intention*[Title/Abstract] OR "intervention*"[Title/Abstract] OR

		"involvement"[Title/Abstract] OR "Knowledge, attitudes and practices"[Title/Abstract] OR "knowledge attitude* practice*"[Title/Abstract] OR "KAP"[Title/Abstract] OR "liability"[Title/Abstract] OR motivat*[Title/Abstract] OR neuroecon*[Title/Abstract] OR "obedience"[Title/Abstract] OR prejudice*[Title/Abstract] OR perception*[Title/Abstract] OR "practices"[Title/Abstract] OR "prompting"[Title/Abstract] OR "priming"[Title/Abstract] OR "prosocial behavior"[Title/Abstract] OR "prosocial behaviour"[Title/Abstract]OR psychosocial*[Title/Abstract] OR "public awareness"[Title/Abstract] OR resilience[Title/Abstract] OR "resistance"[Title/Abstract] OR rationale*[Title/Abstract] OR "reasoning"[Title/Abstract] OR "recognise"[Title/Abstract] OR "recognize"[Title/Abstract] OR "reflexes"[Title/Abstract] OR "reputation"[Title/Abstract] OR respond*[Title/Abstract] OR reponse*[Title/Abstract] OR "responsibility"[Title/Abstract] OR "risk perception"[Title/Abstract:~3] OR "risks perception"[Title/Abstract:~3] OR "risk perceptions"[Title/Abstract:~3] OR "risks perceptions"[Title/Abstract:~3] OR "risk perceive"[Title/Abstract:~3] OR "risks perceive"[Title/Abstract:~3] OR "risk perceives"[Title/Abstract:~3] OR "risks perceives"[Title/Abstract:~3] OR "risk perceived"[Title/Abstract:~3] OR "risks perceived"[Title/Abstract:~3] OR "risk perceiving"[Title/Abstract:~3] OR "risks perceiving"[Title/Abstract:~3] OR "self-efficacy"[Title/Abstract] OR sensibilit*[Title/Abstract] OR "shame"[Title/Abstract] OR "shaming"[Title/Abstract] OR "sharing"[Title/Abstract] OR "social network*"[Title/Abstract] OR strateg*[Title/Abstract] OR stress[Title/Abstract] OR "stigma"[Title/Abstract] OR "surveillance network*"[Title/Abstract] OR "suspicion"[Title/Abstract] OR "tolerance"[Title/Abstract] OR "trust"[Title/Abstract] OR uncertain*[Title/Abstract] OR "under-reporting"[Title/Abstract] OR "underreporting"[Title/Abstract] OR "values"[Title/Abstract] OR "veterinary herd health management"[Title/Abstract] OR "vigilan*"[Title/Abstract] OR "willingness"[Title/Abstract] OR "Psychology"[Mesh] OR "Social Responsibility"[Mesh] OR "Organization and Administration"[Mesh] OR "Altruism"[Mesh] OR "Social Behavior"[Mesh] OR "Helping Behavior"[Mesh] OR "Attitude"[Mesh] OR "Information Avoidance"[Mesh] OR "Communication Barriers"[Mesh] OR "Behavior"[Mesh] OR "Health Belief Model"[Mesh] OR "Budgets"[Mesh] OR "Choice Behavior"[Mesh] OR "Cognitive Psychology"[Mesh] OR "Cognitive Neuroscience"[Mesh] OR "Intersectoral Collaboration"[Mesh] OR "Community Participation"[Mesh] OR "International Cooperation"[Mesh] OR "Cost-Benefit Analysis"[Mesh] OR "Cues"[Mesh] OR "Exploratory Behavior"[Mesh] OR "Decision Making"[Mesh] OR "Emotions"[Mesh] OR "Social Facilitation"[Mesh] OR "Fear"[Mesh] OR "Habits"[Mesh] OR "Help-Seeking Behavior"[Mesh] OR "Instinct"[Mesh] OR

		"Intention"[Mesh] OR "Psychosocial Intervention"[Mesh] OR "Early Medical Intervention"[Mesh] OR "Health Knowledge, Attitudes, Practice"[Mesh] OR "Liability, Legal"[Mesh] OR "Motivation"[Mesh] OR "Prejudice"[Mesh] OR "Perception"[Mesh] OR "Psychosocial Functioning"[Mesh] OR "Resilience, Psychological"[Mesh] OR "Public Opinion"[Mesh] OR "Recognition, Psychology"[Mesh] OR "Reflex"[Mesh] OR "Risk"[Mesh] OR "Health Risk Behaviors"[Mesh] OR "Risk Reduction Behavior"[Mesh] OR "Risk Management"[Mesh] OR "Risk Sharing, Financial"[Mesh] OR "Risk Assessment"[Mesh] OR "Risk Factors"[Mesh] OR "Risk Adjustment"[Mesh] OR "Risk-Taking"[Mesh] OR "Risk Evaluation and Mitigation"[Mesh] OR "Social Perception"[Mesh] OR "Self Efficacy"[Mesh] OR "Shame"[Mesh] OR "Cost Sharing"[Mesh] OR "Social Network Analysis"[Mesh] OR "Social Networking"[Mesh] OR "Adaptation, Psychological"[Mesh] OR "Stress, Psychological"[Mesh] OR "Social Stigma"[Mesh] OR "Community Networks"[Mesh] OR "Trust"[Mesh] OR "Uncertainty"[Mesh] OR "Social Values"[Mesh] OR "Social Norms"[Mesh]
Outcomes 1	Disease reporting	"disease tracking"[Title/Abstract:~3] OR "disease tracker"[Title/Abstract:~3] OR "disease tracked"[Title/Abstract:~3] OR "disease track"[Title/Abstract:~3] OR "disease tracks"[Title/Abstract:~3] OR "diseases tracking"[Title/Abstract:~3] OR "diseases tracker"[Title/Abstract:~3] OR "diseases tracked"[Title/Abstract:~3] OR "diseases track"[Title/Abstract:~3] OR "diseases tracks"[Title/Abstract:~3] OR "diseased tracking"[Title/Abstract:~3] OR "diseased tracker"[Title/Abstract:~3] OR "diseased tracked"[Title/Abstract:~3] OR "diseased track"[Title/Abstract:~3] OR "diseased tracks"[Title/Abstract:~3] OR "disease survey"[Title/Abstract:~3] OR "disease surveys"[Title/Abstract:~3] OR "disease surveying"[Title/Abstract:~3] OR "disease surveyer"[Title/Abstract:~3] OR "disease surveyed"[Title/Abstract:~3] OR "diseases surveying"[Title/Abstract:~3] OR "diseases surveyer"[Title/Abstract:~3] OR "diseases surveyed"[Title/Abstract:~3] OR "diseases survey"[Title/Abstract:~3] OR "diseases surveys"[Title/Abstract:~3] OR "diseased surveying"[Title/Abstract:~3] OR "diseased surveyer"[Title/Abstract:~3] OR "diseased surveyed"[Title/Abstract:~3] OR "diseased survey"[Title/Abstract:~3] OR "diseased surveys"[Title/Abstract:~3] OR "disease questionnaire"[Title/Abstract:~3] OR "diseases questionnaire"[Title/Abstract:~3] OR "diseased questionnaire"[Title/Abstract:~3] OR "disease surveillance"[Title/Abstract:~3] OR "diseases surveillance"[Title/Abstract:~3] OR "diseased surveillance"[Title/Abstract:~3] OR "disease identifing"[Title/Abstract:~3] OR "disease

		identifier"[Title/Abstract:~3] OR "disease identifed"[Title/Abstract:~3] OR "disease identify"[Title/Abstract:~3] OR "disease identifies"[Title/Abstract:~3] OR "diseases identifing"[Title/Abstract:~3] OR "diseases identifier"[Title/Abstract:~3] OR "diseases identifed"[Title/Abstract:~3] OR "diseases identify"[Title/Abstract:~3] OR "diseases identifies"[Title/Abstract:~3] OR "diseased identifing"[Title/Abstract:~3] OR "diseased identifier"[Title/Abstract:~3] OR "diseased identifed"[Title/Abstract:~3] OR "diseased identify"[Title/Abstract:~3] OR "diseased identifies"[Title/Abstract:~3] OR "disease reporting"[Title/Abstract:~3] OR "disease reporter"[Title/Abstract:~3] OR "disease reported"[Title/Abstract:~3] OR "disease report"[Title/Abstract:~3] OR "disease reports"[Title/Abstract:~3] OR "diseases reporting"[Title/Abstract:~3] OR "diseases reporter"[Title/Abstract:~3] OR "diseases reported"[Title/Abstract:~3] OR "diseases report"[Title/Abstract:~3] OR "diseases reports"[Title/Abstract:~3] OR "diseased reporting"[Title/Abstract:~3] OR "diseased reporter"[Title/Abstract:~3] OR "diseased reported"[Title/Abstract:~3] OR "diseased report"[Title/Abstract:~3] OR "diseased reports"[Title/Abstract:~3] OR "disease detecting"[Title/Abstract:~3] OR "disease detection"[Title/Abstract:~3] OR "disease detected"[Title/Abstract:~3] OR "disease detect"[Title/Abstract:~3] OR "disease detects"[Title/Abstract:~3] OR "diseases detecting"[Title/Abstract:~3] OR "diseases detection"[Title/Abstract:~3] OR "diseases detected"[Title/Abstract:~3] OR "diseases detect"[Title/Abstract:~3] OR "diseases detects"[Title/Abstract:~3] OR "diseased detecting"[Title/Abstract:~3] OR "diseased detection"[Title/Abstract:~3] OR "diseased detected"[Title/Abstract:~3] OR "diseased detect"[Title/Abstract:~3] OR "diseased detects"[Title/Abstract:~3] OR "disease controlling"[Title/Abstract:~3] OR "disease controlled"[Title/Abstract:~3] OR "disease control"[Title/Abstract:~3] OR "disease controls"[Title/Abstract:~3] OR "diseases controlling"[Title/Abstract:~3] OR "diseases controlled"[Title/Abstract:~3] OR "diseases control"[Title/Abstract:~3] OR "diseases controls"[Title/Abstract:~3] OR "diseased controlling"[Title/Abstract:~3] OR "diseased controlled"[Title/Abstract:~3] OR "diseased control"[Title/Abstract:~3] OR "diseased controls"[Title/Abstract:~3] OR "disease data collecting"[Title/Abstract:~3] OR "disease data collection"[Title/Abstract:~3] OR "disease data collected"[Title/Abstract:~3] OR "disease data collect"[Title/Abstract:~3] OR "disease data collects"[Title/Abstract:~3] OR "diseases data

		collecting"[Title/Abstract:~3] OR "diseases data collection"[Title/Abstract:~3] OR "diseases data collected"[Title/Abstract:~3] OR "diseases data collect"[Title/Abstract:~3] OR "diseases data collects"[Title/Abstract:~3] OR "diseased data collecting"[Title/Abstract:~3] OR "diseased data collection"[Title/Abstract:~3] OR "diseased data collected"[Title/Abstract:~3] OR "diseased data collect"[Title/Abstract:~3] OR "diseased data collects"[Title/Abstract:~3] OR "disease census"[Title/Abstract:~3] OR "disease censused"[Title/Abstract:~3] OR "disease censusing"[Title/Abstract:~3] OR "disease censuses"[Title/Abstract:~3] OR "diseases censusing"[Title/Abstract:~3] OR "diseases censused"[Title/Abstract:~3] OR "diseases census"[Title/Abstract:~3] OR "diseases censuses"[Title/Abstract:~3] OR "diseased censusing"[Title/Abstract:~3] OR "diseased census"[Title/Abstract:~3] OR "diseased censused"[Title/Abstract:~3] OR "diseased censuses"[Title/Abstract:~3] OR "disease monitor"[Title/Abstract:~3] OR "disease monitored"[Title/Abstract:~3] OR "disease monitoring"[Title/Abstract:~3] OR "disease monitors"[Title/Abstract:~3] OR "diseases monitoring"[Title/Abstract:~3] OR "diseases monitored"[Title/Abstract:~3] OR "diseases monitor"[Title/Abstract:~3] OR "diseases monitors"[Title/Abstract:~3] OR "diseased monitoring"[Title/Abstract:~3] OR "diseased monitor"[Title/Abstract:~3] OR "diseased monitored"[Title/Abstract:~3] OR "diseased monitors"[Title/Abstract:~3] OR "disease communicate"[Title/Abstract:~3] OR "disease communicated"[Title/Abstract:~3] OR "disease communication"[Title/Abstract:~3] OR "disease communicates"[Title/Abstract:~3] OR "disease communicating"[Title/Abstract:~3] OR "disease communications"[Title/Abstract:~3] OR "diseases communicate"[Title/Abstract:~3] OR "diseases communicated"[Title/Abstract:~3] OR "diseases communication"[Title/Abstract:~3] OR "diseases communicates"[Title/Abstract:~3] OR "diseases communicating"[Title/Abstract:~3] OR "diseases communications"[Title/Abstract:~3] OR "diseased communicate"[Title/Abstract:~3] OR "diseased communicated"[Title/Abstract:~3] OR "diseased communication"[Title/Abstract:~3] OR "diseased communicates"[Title/Abstract:~3] OR "diseased communicating"[Title/Abstract:~3] OR "diseased communications"[Title/Abstract:~3] OR "disease record"[Title/Abstract:~3] OR "disease recording"[Title/Abstract:~3]

		OR "disease records"[Title/Abstract:~3] OR "disease recorded"[Title/Abstract:~3] OR "diseases record"[Title/Abstract:~3] OR "diseases recorded"[Title/Abstract:~3] OR "diseases records"[Title/Abstract:~3] OR "diseases recording"[Title/Abstract:~3] OR "diseased record"[Title/Abstract:~3] OR "diseased recorded"[Title/Abstract:~3] OR "diseased records"[Title/Abstract:~3] OR "diseased recording"[Title/Abstract:~3] OR "disease sampling"[Title/Abstract:~3] OR "disease sampled"[Title/Abstract:~3] OR "diseases sampled"[Title/Abstract:~3] OR "diseases sampling"[Title/Abstract:~3] OR "diseased sampled"[Title/Abstract:~3] OR "diseased sampling"[Title/Abstract:~3] OR "disease exchange"[Title/Abstract:~3] OR "disease exchanging"[Title/Abstract:~3] OR "disease exchanges"[Title/Abstract:~3] OR "disease exchanged"[Title/Abstract:~3] OR "diseases exchange"[Title/Abstract:~3] OR "diseases exchanged"[Title/Abstract:~3] OR "diseases exchanges"[Title/Abstract:~3] OR "diseases exchanging"[Title/Abstract:~3] OR "diseased exchange"[Title/Abstract:~3] OR "diseased exchanged"[Title/Abstract:~3] OR "diseased exchanges"[Title/Abstract:~3] OR "diseased exchanging"[Title/Abstract:~3] OR "disease disclose"[Title/Abstract:~3] OR "disease disclosing"[Title/Abstract:~3] OR "disease discloses"[Title/Abstract:~3] OR "disease disclosed"[Title/Abstract:~3] OR "diseases disclose"[Title/Abstract:~3] OR "diseases disclosed"[Title/Abstract:~3] OR "diseases discloses"[Title/Abstract:~3] OR "diseases disclosing"[Title/Abstract:~3] OR "diseased disclose"[Title/Abstract:~3] OR "diseased disclosed"[Title/Abstract:~3] OR "diseased discloses"[Title/Abstract:~3] OR "diseased disclosing"[Title/Abstract:~3] OR "disease notify"[Title/Abstract:~3] OR "disease notifying"[Title/Abstract:~3] OR "disease notification"[Title/Abstract:~3] OR "disease notifications"[Title/Abstract:~3] OR "disease notified"[Title/Abstract:~3] OR "disease notifies"[Title/Abstract:~3] OR "diseases notify"[Title/Abstract:~3] OR "diseases notifying"[Title/Abstract:~3] OR "diseases notification"[Title/Abstract:~3] OR "diseases notifications"[Title/Abstract:~3] OR "diseases notified"[Title/Abstract:~3] OR "diseases notifies"[Title/Abstract:~3] OR "diseased notify"[Title/Abstract:~3] OR "diseased notifying"[Title/Abstract:~3] OR "diseased notification"[Title/Abstract:~3] OR "diseased notifications"[Title/Abstract:~3] OR "diseased notified"[Title/Abstract:~3] OR "diseased notifies"[Title/Abstract:~3]

		OR "disease mapping"[Title/Abstract:~3] OR "disease mapped"[Title/Abstract:~3] OR "diseases mapped"[Title/Abstract:~3] OR "diseases mapping"[Title/Abstract:~3] OR "diseased mapped"[Title/Abstract:~3] OR "diseased mapping"[Title/Abstract:~3] OR "disease screening"[Title/Abstract:~3] OR "disease screened"[Title/Abstract:~3] OR "diseases screening"[Title/Abstract:~3] OR "diseases screened"[Title/Abstract:~3] OR "diseased screening"[Title/Abstract:~3] OR "diseased screened"[Title/Abstract:~3] OR "participatory epidemiology"[Title/Abstract] OR sentinel*[Title/Abstract] OR (("Disease"[Mesh]) AND ("Surveys and Questionnaires"[Mesh] OR "Sentinel Surveillance"[Mesh] OR "Public Health Surveillance"[Mesh] OR "Self Report"[Mesh] OR "Mandatory Reporting"[Mesh] OR "Social Control, Informal"[Mesh] OR "Social Control, Formal"[Mesh] OR "Infection Control"[Mesh] OR "Communicable Disease Control"[Mesh] OR "Behavior Control"[Mesh] OR "Social Control Policies"[Mesh] OR "Data Collection"[Mesh] OR "Censuses"[Mesh] OR "Epidemiological Monitoring"[Mesh] OR "Communication"[Mesh] OR "Records"[Mesh] OR "Sampling Studies"[Mesh] OR "Health Information Exchange"[Mesh] OR "Disclosure"[Mesh] OR "Self Disclosure"[Mesh] OR "Geographic Mapping"[Mesh] OR "Mass Screening"[Mesh] OR "Mandatory Testing"[Mesh])) OR "Disease Notification"[Mesh]
Outcome 2	Animal disease	"notifiable disease*"[Title/Abstract] OR "reportable disease*"[Title/Abstract] OR "animal disease*"[Title/Abstract] OR "sheep disease*"[Title/Abstract] OR "ovine disease*"[Title/Abstract] OR "goat disease*"[Title/Abstract] OR "caprine disease*"[Title/Abstract] OR "canine disease*"[Title/Abstract] OR "dog disease*"[Title/Abstract] OR "cat disease*"[Title/Abstract] OR "feline disease*"[Title/Abstract] OR "poultry disease*"[Title/Abstract] OR "bird disease*"[Title/Abstract] OR "avian disease*"[Title/Abstract] OR "aquatic disease*"[Title/Abstract] OR "fish disease*"[Title/Abstract] OR "swine disease*"[Title/Abstract] OR "porcine disease*"[Title/Abstract] OR "pig disease*"[Title/Abstract] OR "cattle disease*"[Title/Abstract] OR "bovine disease*"[Title/Abstract] OR "horse disease*"[Title/Abstract] OR "livestock disease*"[Title/Abstract] OR zoonotic[Title/Abstract] OR zoonoses[Title/Abstract] OR Akabane[Title/Abstract] OR "Akabane orthobunyavirus"[Title/Abstract] OR "AKAV"[Title/Abstract] OR "Yaba-7 virus"[Title/Abstract] OR "Tinaroo virus"[Title/Abstract] OR "Sabo virus"[Title/Abstract] OR Anthrax[Title/Abstract] OR "Bacillus anthracis"[Title/Abstract] OR Bluetongue[Title/Abstract] OR "blue tongue"[Title/Abstract] OR "Bovine Tuberculosis"[Title/Abstract] OR "Mycobacterium bovis"[Title/Abstract] OR Brucellosis[Title/Abstract] OR "Brucella abortus"[Title/Abstract] OR "Brucella

		melitensis"[Title/Abstract] OR "Brucella suis"[Title/Abstract] OR "Gibralter fever"[Title/Abstract] OR "Malta fever"[Title/Abstract] OR "Cyprus fever"[Title/Abstract] OR "undulant fever"[Title/Abstract] OR "Danube fever"[Title/Abstract] OR "Crimean Congo hemorrhagic fever"[Title/Abstract] OR "Khasan virus"[Title/Abstract] OR "Kodzha virus"[Title/Abstract] OR "CCHFV"[Title/Abstract] OR "HAZV"[Title/Abstract] OR "Hazara virus"[Title/Abstract] OR "KHAV"[Title/Abstract] OR "Eastern Equine encephalomyelitis"[Title/Abstract] OR "Epizootic hemorrhagic disease"[Title/Abstract] OR "epizootic haemorrhagic disease"[Title/Abstract] OR "EHD"[Title/Abstract] OR "Foot-and-Mouth Disease"[Title/Abstract] OR "FMD"[Title/Abstract] OR "hoof and mouth"[Title/Abstract] OR Heartwater[Title/Abstract] OR "Ehrlichia ruminantium"[Title/Abstract] OR "Japanese Encephalitis"[Title/Abstract] OR "Japanese B encephalitis"[Title/Abstract] OR Meliodosis[Title/Abstract] OR Melioidosis[Title/Abstract] OR "Burkholderia pseudomallei"[Title/Abstract] OR "Mycobacterium Tuberculosis Complex"[Title/Abstract] OR "M. caprae"[Title/Abstract] OR "Mycobacterium caprae"[Title/Abstract] OR "M. tuberculosis"[Title/Abstract] OR "Mycobacterium tuberculosis"[Title/Abstract] OR Screwworm[Title/Abstract] OR "screw worm"[Title/Abstract] OR "Cochliomyia hominivorax"[Title/Abstract] OR "Chrysomya bezziana"[Title/Abstract] OR Pseudorabies[Title/Abstract] OR "pseudo-rabies"[Title/Abstract] OR "Aujeszky disease"[Title/Abstract] OR "Aujeszky's disease"[Title/Abstract] OR Rabies[Title/Abstract] OR "Rift Valley Fever"[Title/Abstract] OR "Belterra virus"[Title/Abstract] OR "Rift Valley phlebovirus"[Title/Abstract] OR "Icoaraci virus"[Title/Abstract] OR Rinderpest[Title/Abstract] OR "RDV"[Title/Abstract] OR "RPV"[Title/Abstract] OR "SARS-CoV-2"[Title/Abstract] OR Surra[Title/Abstract] OR "equine trypanosomosis"[Title/Abstract] OR "Trypanosoma evansi"[Title/Abstract] OR Trichinellosis[Title/Abstract] OR trichinelliasis[Title/Abstract] OR Trichinella[Title/Abstract] OR "Vesicular stomatitis"[Title/Abstract] OR "West Nile virus"[Title/Abstract] OR "Kunjin virus"[Title/Abstract] OR "West Nile flavivirus"[Title/Abstract] OR "WNV"[Title/Abstract] OR "KUNV"[Title/Abstract] OR "Duck viral hepatitis"[Title/Abstract] OR "duck virus hepatitis"[Title/Abstract] OR "Fowl typhoid"[Title/Abstract] OR "Salmonella entirica"[Title/Abstract] OR "Salmonella Gallinarum"[Title/Abstract] OR "avian influenza"[Title/Abstract] OR "bird flu"[Title/Abstract] OR "avian flu"[Title/Abstract] OR "influenza in birds"[Title/Abstract] OR "Highly pathogenic avian influenza"[Title/Abstract] OR "HPAI"[Title/Abstract] OR "Low pathogenic avian influenza"[Title/Abstract] OR "LPAI"[Title/Abstract] OR "Pullorum"[Title/Abstract] OR "Turkey rhinotracheitis"[Title/Abstract] OR "avian

		metapneumovirus"[Title/Abstract] OR Metapneumovirus[Title/Abstract] OR "TRTV"[Title/Abstract] OR "AMPV"[Title/Abstract] OR "APV"[Title/Abstract] OR "Avian pneumovirus"[Title/Abstract] OR "Newcastle disease"[Title/Abstract] OR "Avian orthoavulavirus"[Title/Abstract] OR "Avian paramyxovirus"[Title/Abstract] OR "NDV"[Title/Abstract] OR "APMV-1"[Title/Abstract] OR "Bovine babesiosis"[Title/Abstract] OR "Babesia bovis"[Title/Abstract] OR "B.bigemina"[Title/Abstract] OR "Babesia bigemina"[Title/Abstract] OR Babesiosis[Title/Abstract] OR "Bovine spongiform encephalopathy"[Title/Abstract] OR "BSE"[Title/Abstract] OR "prion disease*"[Title/Abstract] OR "Contagious bovine pleuropneumonia"[Title/Abstract] OR Pleuropneumonia[Title/Abstract] OR "Mycoplasma mycoides mycoides"[Title/Abstract] OR "Hemorrhagic septicemia"[Title/Abstract] OR "Pasteurella multocida"[Title/Abstract] OR "Lumpy skin disease"[Title/Abstract] OR Theileriosis[Title/Abstract] OR "Theileria annulata"[Title/Abstract] OR "T. annulata"[Title/Abstract] OR "Theileria parva"[Title/Abstract] OR "T.parva"[Title/Abstract] OR Trichomoniasis[Title/Abstract] OR Trypanosomosis[Title/Abstract] OR "Contagious caprine pleuropneumonia"[Title/Abstract] OR Mange[Title/Abstract] OR "Mite Infestation*"[Title/Abstract] OR "sheep scab"[Title/Abstract] OR "Sarcoptes scabiei var ovis"[Title/Abstract] OR "Chorioptes bovis"[Title/Abstract] OR "Psoroptes ovis"[Title/Abstract] OR "Psoroptes cuniculi"[Title/Abstract] OR "Psoregates ovis"[Title/Abstract] OR "Nairobi sheep disease"[Title/Abstract] OR "Peste des petitis ruminants"[Title/Abstract] OR Scrapie[Title/Abstract] OR "Sheep pox"[Title/Abstract] OR "goat pox"[Title/Abstract] OR "African horse sickness"[Title/Abstract] OR "Contagious equine metritis"[Title/Abstract] OR "CEM"[Title/Abstract] OR "Taylorella equigenitalis"[Title/Abstract] OR Dourine[Title/Abstract] OR "Trypanasoma equiperdum"[Title/Abstract] OR "Equine infectious anemia"[Title/Abstract] OR "Equine piroplasmosis"[Title/Abstract] OR babesiosis[Title/Abstract] OR "Theileria equi"[Title/Abstract] OR "Babesia caballi"[Title/Abstract] OR "Equine rhinopneumonitis equine herpesvirus-1 myeloencephalopathy"[Title/Abstract] OR "Equine Herpesvirus Myeloencephalopathy"[Title/Abstract] OR Encephalomyelitis[Title/Abstract] OR "EHV1-EHM"[Title/Abstract] OR Glanders[Title/Abstract] OR "Burkholderia mallei"[Title/Abstract] OR Hendra[Title/Abstract] OR "Venezuelan Equine encephalomyelitis"[Title/Abstract] OR VEE[Title/Abstract] OR "Western Equine encephalomyelitis"[Title/Abstract] OR "Chronic wasting disease"[Title/Abstract] OR CWD[Title/Abstract] OR Myxomatosis[Title/Abstract] OR "Rabbit hemorrhagic disease"[Title/Abstract] OR "swine fever"[Title/Abstract] OR "hog cholera"[Title/Abstract] OR "Nipah virus"[Title/Abstract] OR "Swine vesicular disease"[Title/Abstract] OR "Camel pox"[Title/Abstract] OR

		(dromedary camel*[Title/Abstract] OR (respiratory[Title/Abstract] AND coronavirus[Title/Abstract] OR MERS CoV[Title/Abstract])) OR Leishmaniasis[Title/Abstract] OR exanthema[Title/Abstract] OR "Senecavirus A"[Title/Abstract] OR "Seneca Valley virus"[Title/Abstract] OR "Echinococcus Granulosis"[Title/Abstract] OR Hydatidosis[Title/Abstract] OR Echinococcosis[Title/Abstract] OR "Echinococcus Multiocularis"[Title/Abstract] OR "Johne's disease"[Title/Abstract] OR "Johnes Disease"[Title/Abstract] OR "Mycobacterium avium paratuberculosis"[Title/Abstract] OR "Paratuberculosis"[Title/Abstract] OR "Q Fever"[Title/Abstract] OR "Coxiella burnetti"[Title/Abstract] OR Tularemia[Title/Abstract] OR "Francisella tularensis"[Title/Abstract] OR "Avian chlamydiosis"[Title/Abstract] OR "Chlamydia psittaci"[Title/Abstract] OR Psittacosis[Title/Abstract] OR "Avian infectious bronchitis"[Title/Abstract] OR "Avian infectious laryngotracheitis"[Title/Abstract] OR "Avian mycoplasmosis"[Title/Abstract] OR "Mycoplasma gallisepticum"[Title/Abstract] OR "Mycoplasma synoviae"[Title/Abstract] OR "Infectious bursal disease"[Title/Abstract] OR "Gumboro disease"[Title/Abstract] OR Anaplasmosis[Title/Abstract] OR "Anaplasma marginale"[Title/Abstract] OR "A. marginale"[Title/Abstract] OR "Anaplasma central"[Title/Abstract] OR "Bovine genital campylobacteriosis"[Title/Abstract] OR "Campylobacter fetus venerealis"[Title/Abstract] OR "Bovine viral diarrhea"[Title/Abstract] OR "BVD"[Title/Abstract] OR "mucosal disease"[Title/Abstract] OR "Enzootic bovine leucosis"[Title/Abstract] OR "BLV"[Title/Abstract] OR "Infectious bovine rhinotracheitis"[Title/Abstract] OR "infectious pustular vulvovaginitis"[Title/Abstract] OR "IBR"[Title/Abstract] OR "IPV"[Title/Abstract] OR "IBR/IPV"[Title/Abstract] OR "Malignant catarrhal fever"[Title/Abstract] OR "Malignant Catarrh"[Title/Abstract] OR "Caprine arthritis encephalitis"[Title/Abstract] OR "CAE"[Title/Abstract] OR Encephalitis[Title/Abstract] OR "Contagious agalactia"[Title/Abstract] OR "Mycoplasma agalactiae"[Title/Abstract] OR "Mycoplasma Capricolum capricolum"[Title/Abstract] OR "Mycoplasma putrefaciens"[Title/Abstract] OR "Mycoplasma mycoides mycoides LC"[Title/Abstract] OR "M. Capricolum capricolum"[Title/Abstract] OR "M. putrefaciens"[Title/Abstract] OR "M. mycoides mycoides"[Title/Abstract] OR "M. mycoides mycoides LC"[Title/Abstract] OR "Enzootic abortion of ewes"[Title/Abstract] OR "ovine chlamydiosis"[Title/Abstract] OR "Chlamydophila abortus"[Title/Abstract] OR "Maedi-visna/ovine progressive pneumonia"[Title/Abstract] OR "Ovine epididymitis"[Title/Abstract] OR "Brucella ovis infection"[Title/Abstract] OR Epididymitis[Title/Abstract] OR Salmonellosis[Title/Abstract] OR Salmonella[Title/Abstract] OR "Equine influenza"[Title/Abstract] OR "Equine rhinopneumonitis"[Title/Abstract] OR "EHV-

		1"[Title/Abstract] OR "Herpesvirus 1, Equid"[Title/Abstract] OR "Equine viral arteritis"[Title/Abstract] OR "Equartevirus"[Title/Abstract] OR "EVA"[Title/Abstract] OR "Pigeon fever"[Title/Abstract] OR "Corynebacterium pseudotuberculosis"[Title/Abstract] OR "ulcerative lymphangitis"[Title/Abstract] OR Strangles[Title/Abstract] OR "Streptococcus equi"[Title/Abstract] OR "Porcine Cysticercosis"[Title/Abstract] OR "Taenia solium"[Title/Abstract] OR Cysticercosis[Title/Abstract] OR "Porcine reproductive and respiratory syndrome"[Title/Abstract] OR "PRRS"[Title/Abstract] OR "Transmissible gastroenteritis"[Title/Abstract] OR "TGE"[Title/Abstract] OR "Batrachochytrium dendrobatidis"[Title/Abstract] OR Batrachochytrium[Title/Abstract] OR "Batrachochytrium salamandrivoran"[Title/Abstract] OR Ranavirus[Title/Abstract] OR "Acute hepatopancreatic necrosis disease"[Title/Abstract] OR "Vibrio parahaemolyticus pVA-1 plasmid"[Title/Abstract] OR "Vibrio parahaemolyticus"[Title/Abstract] OR "Crayfish plague"[Title/Abstract] OR "Aphanomyces astaci"[Title/Abstract] OR "Decapod iridescent virus"[Title/Abstract] OR "DIV1"[Title/Abstract] OR "Infectious hypodermal and hematopoietic necrosis"[Title/Abstract] OR "IHHN"[Title/Abstract] OR "Infectious myonecrosis"[Title/Abstract] OR "Necrotizing hepatopancreatitis"[Title/Abstract] OR "Candidatus Hepatobacter penaei"[Title/Abstract] OR "Taura syndrome"[Title/Abstract] OR "White spot disease"[Title/Abstract] OR "white spot syndrome virus"[Title/Abstract] OR "White tail disease"[Title/Abstract] OR "Hypodermic and hematopoietic necrosis baculovirus"[Title/Abstract] OR "White spot baculovirus"[Title/Abstract] OR "WSSV"[Title/Abstract] OR "Chinese baculo-like virus"[Title/Abstract] OR "White spot bacilliform virus"[Title/Abstract] OR "Macrobrachium rosenbergii nodavirus"[Title/Abstract] OR "Yellow head"[Title/Abstract] OR "Roniviridae"[Title/Abstract] OR "Epizootic hematopoietic necrosis disease"[Title/Abstract] OR "Epizootic ulcerative syndrome"[Title/Abstract] OR "EUS"[Title/Abstract] OR "Aphanomyces invadans"[Title/Abstract] OR Gyrodactylosis[Title/Abstract] OR "Gyrodactylus salaris"[Title/Abstract] OR "Infectious haematopoietic necrosis"[Title/Abstract] OR "IHN"[Title/Abstract] OR "Infectious salmon anemia"[Title/Abstract] OR "isavirus"[Title/Abstract] OR "ISA"[Title/Abstract] OR "HPR0"[Title/Abstract] OR "HPR-deleted"[Title/Abstract] OR Alphavirus[Title/Abstract] OR "Red sea bream iridoviral disease"[Title/Abstract] OR "Spring viremia"[Title/Abstract] OR Viremia[Title/Abstract] OR "Tilapia Lake Virus"[Title/Abstract] OR "Viral hemorrhagic septicemia"[Title/Abstract] OR "VHS"[Title/Abstract] OR "abalone herpes virus"[Title/Abstract] OR "Abalone viral ganglioneuritis"[Title/Abstract] OR "Abalone herpesvirus"[Title/Abstract] OR Bonamiosis[Title/Abstract] OR "B.

		exitiosa"[Title/Abstract] OR "B. ostreae"[Title/Abstract] OR "Bonamia exitosa"[Title/Abstract] OR "Bonamia ostreae"[Title/Abstract] OR Haplosporida[Title/Abstract] OR "Marteilia refringents"[Title/Abstract] OR "Perkinsus olseni"[Title/Abstract] OR "Xenohaliotis californiensis"[Title/Abstract] OR "Koi herpesvirus disease"[Title/Abstract] OR "Perkinsus marinus"[Title/Abstract] OR "Boil disease"[Title/Abstract] OR "Bubble disease"[Title/Abstract] OR "Gill disease"[Title/Abstract] OR "Peduncle disease"[Title/Abstract] OR "Redmouth disease"[Title/Abstract] OR "Yersinia ruckeri"[Title/Abstract] OR "Ulcerative dermal necrosis"[Title/Abstract] OR Vibriosis[Title/Abstract] OR "Whirling disease"[Title/Abstract] OR "Myxobolus cerebralis"[Title/Abstract] OR "Tropilaelaps"[Title/Abstract] OR "Acarapisosis"[Title/Abstract] OR "Acarapis woodi"[Title/Abstract] OR "Paenibacillus larvae"[Title/Abstract] OR "Deformed Wing Virus, Variant C"[Title/Abstract] OR "DWV-C"[Title/Abstract] OR "European foulbrood"[Title/Abstract] OR "Melissococcus plutonius"[Title/Abstract] OR "Slow bee paralysis virus"[Title/Abstract] OR "SBPV"[Title/Abstract] OR "Small hive beetle infestation"[Title/Abstract] OR "Aethina tumida"[Title/Abstract] OR "Varroosis of honey bees"[Title/Abstract] OR Varroa[Title/Abstract] OR Varroidae[Title/Abstract] OR "Sheep Diseases"[Mesh] OR "Goat Diseases"[Mesh] OR "Dog Diseases"[Mesh] OR "Cat Diseases"[Mesh] OR "Poultry Diseases"[Mesh] OR "Bird Diseases"[Mesh] OR "Animal Diseases"[Mesh] OR "Swine Diseases"[Mesh] OR "Cattle Diseases"[Mesh] OR "Fish Diseases"[Mesh] OR "Horse Diseases"[Mesh] OR "Zoonoses"[Mesh] OR "Anthrax"[Mesh] OR "Bluetongue"[Mesh] OR "Tuberculosis, Bovine"[Mesh] OR "Brucellosis, Bovine"[Mesh] OR "Hemorrhagic Fever Virus, Crimean-Congo"[Mesh] OR "Hemorrhagic Fever, Crimean"[Mesh] OR "Encephalomyelitis, Eastern Equine"[Mesh] OR "Encephalitis Virus, Eastern Equine"[Mesh] OR "Hemorrhagic Disease Virus, Epizootic"[Mesh] OR "Foot-and-Mouth Disease"[Mesh] OR "Foot-and-Mouth Disease Virus"[Mesh] OR "Heartwater Disease"[Mesh] OR "Ehrlichia ruminantium"[Mesh] OR "Encephalitis, Japanese"[Mesh] OR "Encephalitis Virus, Japanese"[Mesh] OR "Melioidosis"[Mesh] OR "Burkholderia Infections"[Mesh] OR "Mycobacterium tuberculosis"[Mesh] OR "Screw Worm Infection"[Mesh] OR "Pseudorabies"[Mesh] OR "Rabies"[Mesh] OR "Rabies virus"[Mesh] OR "Rift Valley Fever"[Mesh] OR "Rift Valley fever virus"[Mesh] OR "Phlebovirus"[Mesh] OR "Rinderpest virus"[Mesh] OR "Rinderpest"[Mesh] OR "SARS-CoV-2"[Mesh] OR "Trypanosomiasis"[Mesh] OR "Trypanosomiasis, African"[Mesh] OR "Trypanosomiasis, Bovine"[Mesh] OR "Dourine"[Mesh] OR "Trichinellosis"[Mesh] OR "Vesicular stomatitis Indiana virus"[Mesh] OR "Vesicular stomatitis New Jersey virus"[Mesh] OR "Vesicular Stomatitis"[Mesh] OR "West Nile Fever"[Mesh] OR "West Nile virus"[Mesh] OR "Hepatitis, Viral, Animal"[Mesh] OR "Salmonella

		enterica"[Mesh] OR "Typhoid Fever"[Mesh] OR "Influenza in Birds"[Mesh] OR "Influenza A virus"[Mesh] OR "Metapneumovirus"[Mesh] OR "Newcastle disease virus"[Mesh] OR "Newcastle Disease"[Mesh] OR "Avulavirus"[Mesh] OR "Babesiosis"[Mesh] OR "Encephalopathy, Bovine Spongiform"[Mesh] OR "Prion Diseases"[Mesh] OR "Pleuropneumonia, Contagious"[Mesh] OR "Mycoplasma"[Mesh] OR "Hemorrhagic Septicemia, Viral"[Mesh] OR "Hemorrhagic Septicemia"[Mesh] OR "Pasteurella multocida"[Mesh] OR "Pasteurella Infections"[Mesh] OR "Lumpy Skin Disease"[Mesh] OR "Lumpy skin disease virus"[Mesh] OR "Theileriasis"[Mesh] OR "Trichomonas Infections"[Mesh] OR "Mite Infestations"[Mesh] OR "Scabies"[Mesh] OR "Psoroptidae"[Mesh] OR "Nairobi sheep disease virus"[Mesh] OR "Nairobi Sheep Disease"[Mesh] OR "Peste-des-Petits-Ruminants"[Mesh] OR "Peste-des-petits-ruminants virus"[Mesh] OR "Scrapie"[Mesh] OR "Capripoxvirus"[Mesh] OR "African Horse Sickness Virus"[Mesh] OR "African Horse Sickness"[Mesh] OR "Taylorella equigenitalis"[Mesh] OR "Infectious Anemia Virus, Equine"[Mesh] OR "Equine Infectious Anemia"[Mesh] OR "Herpesvirus 4, Equid"[Mesh] OR "Encephalomyelitis, Equine"[Mesh] OR "Glanders"[Mesh] OR "Hendra Virus"[Mesh] OR "Henipavirus Infections"[Mesh] OR "Encephalomyelitis"[Mesh] OR "Encephalomyelitis, Eastern Equine"[Mesh] OR "Encephalomyelitis, Western Equine"[Mesh] OR "Encephalomyelitis, Venezuelan Equine"[Mesh] OR "Encephalomyelitis, Enzootic Porcine"[Mesh] OR "Encephalomyelitis Virus, Avian"[Mesh] OR "Wasting Disease, Chronic"[Mesh] OR "Myxoma virus"[Mesh] OR "Myxomatosis, Infectious"[Mesh] OR "Hemorrhagic Disease Virus, Rabbit"[Mesh] OR "African Swine Fever"[Mesh] OR "African Swine Fever Virus"[Mesh] OR "Classical Swine Fever Virus"[Mesh] OR "Classical Swine Fever"[Mesh] OR "Nipah Virus"[Mesh] OR "Swine Vesicular Disease"[Mesh] OR "Leishmaniasis"[Mesh] OR "Exanthema"[Mesh] OR "Picornaviridae"[Mesh] OR "Echinococcus"[Mesh] OR "Echinococcus granulosus"[Mesh] OR "Paratuberculosis"[Mesh] OR "Q Fever"[Mesh] OR "Tularemia"[Mesh] OR "Chlamydophila psittaci"[Mesh] OR "Psittacosis"[Mesh] OR "Infectious bronchitis virus"[Mesh] OR "Iltovirus"[Mesh] OR "Mycoplasma Infections"[Mesh] OR "Mycoplasma gallisepticum"[Mesh] OR "Mycoplasma synoviae"[Mesh] OR "Infectious bursal disease virus"[Mesh] OR "Anaplasmosis"[Mesh] OR "Anaplasma marginale"[Mesh] OR "Campylobacter Infections"[Mesh] OR "Bovine Virus Diarrhea-Mucosal Disease"[Mesh] OR "Diarrhea Viruses, Bovine Viral"[Mesh] OR "Diarrhea Virus 1, Bovine Viral"[Mesh] OR "Diarrhea Virus 2, Bovine Viral"[Mesh] OR "Enzootic Bovine Leukosis"[Mesh] OR "Leukemia Virus, Bovine"[Mesh] OR "Infectious Bovine Rhinotracheitis"[Mesh] OR "Herpesvirus 1, Bovine"[Mesh] OR "Malignant Catarrh"[Mesh] OR "Arthritis-Encephalitis Virus, Caprine"[Mesh] OR "Encephalitis"[Mesh] OR "Mycoplasma

		agalactiae"[Mesh] OR "Chlamydia"[Mesh] OR "Pneumonia, Progressive Interstitial, of Sheep"[Mesh] OR "Epididymitis"[Mesh] OR "Brucella ovis"[Mesh] OR "Salmonella Infections"[Mesh] OR "Salmonella"[Mesh] OR "Influenza A Virus, H3N8 Subtype"[Mesh] OR "Herpesvirus 4, Equid"[Mesh] OR "Herpesvirus 1, Meleagrid"[Mesh] OR "Herpesvirus 1, Suid"[Mesh] OR "Herpesvirus 1, Equid"[Mesh] OR "Herpesvirus 1, Canid"[Mesh] OR "Herpesvirus 2, Gallid"[Mesh] OR "Herpesvirus 1, Gallid"[Mesh] OR "Equartevirus"[Mesh] OR "Corynebacterium pseudotuberculosis"[Mesh] OR "Streptococcus equi"[Mesh] OR "Cysticercosis"[Mesh] OR "Taenia solium"[Mesh] OR "Porcine Reproductive and Respiratory Syndrome"[Mesh] OR "Porcine respiratory and reproductive syndrome virus"[Mesh] OR "Transmissible gastroenteritis virus"[Mesh] OR "Gastroenteritis, Transmissible, of Swine"[Mesh] OR "Batrachochytrium"[Mesh] OR "Ranavirus"[Mesh] OR "Vibrio parahaemolyticus"[Mesh] OR "Aphanomyces"[Mesh] OR "Densovirinae"[Mesh] OR "Taura syndrome virus" [Supplementary Concept] OR "Dicistroviridae"[Mesh] OR "Baculoviridae"[Mesh] OR "Roniviridae"[Mesh] OR "Infectious hematopoietic necrosis virus"[Mesh] OR "Epizootic haematopoietic necrosis virus" [Supplementary Concept] OR "Isavirus"[Mesh] OR "Alphavirus"[Mesh] OR "Alphavirus Infections"[Mesh] OR "Viremia"[Mesh] OR "Hemorrhagic Septicemia, Viral"[Mesh] OR "Hemorrhagic Septicemia"[Mesh] OR "Haplosporida"[Mesh] OR "Amoebic gill disease" [Supplementary Concept] OR "Yersinia ruckeri"[Mesh] OR "Vibrio Infections"[Mesh] OR "Paenibacillus larvae"[Mesh] OR "Deformed wing virus" [Supplementary Concept] OR "Melissococcus plutonius" [Supplementary Concept] OR "Acute bee paralysis virus" [Supplementary Concept] OR "Varroidae"[Mesh]

Appendix D

Details of the Theoretical Domain Framework

Table D1. Theoretical Domain Framework domains, definitions, and theoretical constructs (Cane et al., 2012).

No.	Domain	Definition	Theoretical constructs
1	Knowledge	An awareness of the existence of something.	• Knowledge (including knowledge of condition /scientific rationale) • Procedural knowledge • Knowledge of task environment
2	Skills	An ability or proficiency acquired through practice.	• Skills • Skills development • Competence • Ability • Interpersonal skills • Practice • Skill assessment
3	Social/professional role and identity	A coherent set of behaviors and displayed personal qualities of an individual in a social or work setting.	• Professional identity • Professional role • Social identity • Identity • Professional boundaries • Professional confidence • Group identity • Leadership • Organizational commitment
4	Beliefs about capabilities	Acceptance of the truth, reality, or validity about an ability, talent, or facility that a person can put to constructive use.	• Self-confidence • Perceived competence • Self-efficacy • Perceived behavioral control • Beliefs • Self-esteem • Empowerment • Professional confidence
5	Optimism	The confidence that things will happen for the best or	• Optimism • Pessimism • Unrealistic optimism

		that desired goals will be attained.	• Identity
6	Beliefs about consequences	Acceptance of the truth, reality, or validity about outcomes of a behavior in a given situation.	• Beliefs • Outcome expectancies • Characteristics of outcome expectancies • Anticipated regret • Consequents
7	Reinforcement	Increasing the probability of a response by arranging a dependent relationship, or contingency, between the response and a given stimulus.	• Rewards (proximal / distal, valued / not valued, probable / improbable) • Incentives • Punishment • Consequents • Reinforcement • Contingencies • Sanctions
8	Intentions	A conscious decision to perform a behavior or a resolve to act in a certain way.	• Stability of intentions • Stages of change model • Transtheoretical model and stages of change
9	Goals	Mental representations of outcomes or end states that an individual wants to achieve	• Goals (distal / proximal) • Goal priority • Goal / target setting • Goals (autonomous / controlled) • Action planning • Implementation intention
10	Memory, attention, and decision processes	The ability to retain information, focus selectively on aspects of the environment and choose between two or more alternatives.	• Memory • Attention • Attention control • Decision making • Cognitive overload / tiredness
11	Environmental context and resources	Any circumstance of a person's situation or environment that discourages or encourages the development of skills and abilities, independence, social competence, and adaptive behavior.	• Environmental stressors • Resources / material resources • Organizational culture /climate • Salient events / critical incidents

			• Person x environment interaction • Barriers and facilitators
12	Social influences	Those interpersonal processes that can cause individuals to change their thoughts, feelings, or behaviors.	• Social pressure • Social norms • Group conformity • Social comparisons • Group norms • Social support • Power • Intergroup conflict • Alienation • Group identity • Modelling
13	Emotion	A complex reaction pattern, involving experiential, behavioral, and physiological elements, by which the individual attempts to deal with a personally significant matter or event.	• Fear • Anxiety • Affect • Stress • Depression • Positive / negative affect • Burn-out
14	Behavioral regulation	Anything aimed at managing or changing objectively observed or measured actions.	• Self-monitoring • Breaking habit • Action planning

Appendix E

Details of the COM-B model

Table E1. COM-B model components and definitions (Michie et al., 2014).

No.	Component	Definition
1	Physical capability	Physical skill, strength or stamina.
2	Psychological capability	Knowledge or psychological skills, strength or stamina to engage in the necessary mental processes.
3	Physical opportunity	Opportunity afforded by the environment involving time, resources, locations, cues, physical 'affordance'.
4	Social opportunity	Opportunity afforded by interpersonal influences, social cues and cultural norms that influence the way that we think about things, e.g. the words and concepts that make up our language.
5	Reflective motivation	Reflective processes involving plans (self-conscious intentions) and evaluations (beliefs about that is good and bad).
6	Automatic motivation	Automatic processes involving emotional reactions, desires (wants and needs), impulses, inhibitions, drive states and reflex responses.

Appendix F

Details of the Behavior Change Techniques Taxonomy (Version 1)

Table F1. Behavior Change Techniques labels, groups, and definitions (Michie et al., 2013).

No.	Label	Definition
1. Goals and planning		
1.1	***Goal setting (behavior)***	Set or agree on a goal defined in terms of the behavior to be achieved
1.2	***Problem solving***	Analyze, or prompt the person to analyze, factors influencing the behavior and generate or select strategies that include overcoming barriers and/or increasing facilitators (includes '**Relapse Prevention**' *and* '**Coping Planning**')
1.3	***Goal setting (outcome)***	Set or agree on a goal defined in terms of a positive **outcome** of wanted behavior
1.4	***Action planning***	Prompt detailed planning of performance of the behavior (must include at least one of context, frequency, duration and intensity). Context may be environmental (physical or social) or internal (physical, emotional or cognitive) (includes '**Implementation Intentions**')
1.5	***Review behavior goal(s)***	Review behavior goal(s) jointly with the person and consider modifying goal(s) or behavior change strategy in light of achievement. This may lead to re-setting the same goal, a small change in that goal or setting a new goal instead of (or in addition to) the first, or no change
1.6	***Discrepancy between current behavior and goal***	Draw attention to discrepancies between a person's current behavior (in terms of the *form, frequency, duration, or intensity* of that behavior) and the person's previously set outcome goals, behavioral goals or action plans (goes beyond self-monitoring of behavior)
1.7	***Review outcome goal(s)***	Review outcome goal(s) jointly with the person and consider modifying goal(s) in light of achievement. This may lead to re-setting the same goal, a small change in that goal or setting a new goal instead of, or in addition to the first
1.8	***Behavioral contract***	Create a written specification of the behavior to be performed, agreed on by the person, and witnessed by another
1.9	***Commitment***	Ask the person to affirm or reaffirm statements indicating commitment to change the behavior

No.	Label	Definition
2. Feedback and monitoring		
2.1	***Monitoring of behavior by others without feedback***	Observe or record behavior with the person's knowledge as part of a behavior change strategy
2.2	***Feedback on behavior***	Monitor and provide informative or evaluative feedback on performance of the behavior *(e.g. form, frequency, duration, intensity)*
2.3	***Self-monitoring of behavior***	Establish a method for the person to monitor and record their behavior(s) as part of a behavior change strategy
2.4	***Self-monitoring of outcome(s) of behavior***	Establish a method for the person to monitor and record the **outcome(s)** of their behavior as part of a behavior change strategy
2.5	***Monitoring outcome(s) of behavior by others without feedback***	Observe or record outcomes of behavior with the person's knowledge as part of a behavior change strategy
2.6	***Biofeedback***	Provide feedback about the body *(e.g. physiological or biochemical state)* using an external monitoring device as part of a behavior change strategy
2.7	***Feedback on outcome(s) of behavior***	Monitor and provide feedback on the outcome of performance of the behavior
3. Social support		
3.1	***Social support (unspecified)***	Advise on, arrange or provide social support *(e.g. from friends, relatives, colleagues,' buddies' or staff)* or non-contingent praise or reward for performance of the behavior. It includes encouragement and counselling, but only when it is directed at the **behavior**
3.2	***Social support (practical)***	Advise on, arrange, or provide **practical** help *(e.g. from friends, relatives, colleagues, 'buddies' or staff)* for performance of the behavior
3.3	***Social support (emotional)***	Advise on, arrange, or provide **emotional** social support *(e.g. from friends, relatives, colleagues, 'buddies' or staff)* for performance of the behavior
4. Shaping knowledge		
4.1	***Instruction on how to perform a behavior***	Advise or agree on how to perform the behavior (includes '**Skills training**')
4.2	***Information about antecedents***	Provide information about antecedents (*e.g. social and environmental situations and events, emotions, cognitions)* that reliably predict performance of the behavior

No.	Label	Definition
4.3	***Re-attribution***	Elicit perceived causes of behavior and suggest alternative explanations *(e.g. external or internal and stable or unstable)*
4.4	***Behavioral experiments***	Advise on how to identify and test hypotheses about the behavior, its causes and consequences, by collecting and interpreting data
5. Natural consequences		
5.1	***Information about health consequences***	Provide information (e.g. written, verbal, visual) about health consequences of performing the behavior
5.2	***Salience of consequences***	Use methods specifically designed to **emphasize** the consequences of performing the behavior with the aim of making them more memorable (goes beyond informing about consequences)
5.3	***Information about social and environmental consequences***	Provide information (e.g. written, verbal, visual) about social and environmental consequences of performing the behavior
5.4	***Monitoring of emotional consequences***	Prompt assessment of **feelings** after attempts at performing the behavior
5.5	***Anticipated regret***	Induce or raise awareness of expectations of future regret about performance of the unwanted behavior
5.6	***Information about emotional consequences***	Provide information (e.g. written, verbal, visual) about emotional consequences of performing the behavior
6. Comparison of behavior		
6.1	***Demonstration of the behavior***	Provide an observable sample of the performance of the behavior, directly in person or indirectly e.g. via film, pictures, for the person to aspire to or imitate (includes '**Modelling**').
6.2	***Social comparison***	Draw attention to others' performance to allow comparison with the person's own performance *Note: being in a group setting does not necessarily mean that social comparison is actually taking place*
6.3	***Information about others' approval***	Provide information about what other people think about the behavior. The information clarifies whether others will like, approve or disapprove of what the person is doing or will do
7. Associations		

No.	Label	Definition
7.1	***Prompts/cues***	Introduce or define environmental or social stimulus with the purpose of prompting or cueing the behavior. The prompt or cue would normally occur at the time or place of performance
7.2	***Cue signaling reward***	Identify an environmental stimulus that reliably predicts that reward will follow the behavior (includes ***'*****Discriminative cue'**)
7.3	***Reduce prompts/cues***	Withdraw gradually prompts to perform the behavior (includes ***'*****Fading'**)
7.4	***Remove access to the reward***	Advise or arrange for the person to be separated from situations in which unwanted behavior can be rewarded in order to reduce the behavior (includes ***'*****Time out'**)
7.5	***Remove aversive stimulus***	Advise or arrange for the removal of an aversive stimulus to facilitate behavior change (includes ***'*****Escape learning'**)
7.6	***Satiation***	Advise or arrange repeated exposure to a stimulus that reduces or extinguishes a drive for the unwanted behavior
7.7	***Exposure***	Provide systematic confrontation with a feared stimulus to reduce the response to a later encounter
7.8	***Associative learning***	Present a neutral stimulus jointly with a stimulus that already elicits the behavior repeatedly until the neutral stimulus elicits that behavior (includes ***'*****Classical/Pavlovian Conditioning'**)
8. Repetition and substitution		
8.1	***Behavioral practice/ rehearsal***	Prompt practice or rehearsal of the performance of the behavior one or more times in a context or at a time when the performance may not be necessary, in order to increase habit and skill
8.2	***Behavior substitution***	Prompt substitution of the unwanted behavior with a wanted or neutral behavior
8.3	***Habit formation***	Prompt rehearsal and repetition of the behavior in the same context repeatedly so that the context elicits the behavior
8.4	***Habit reversal***	Prompt rehearsal and repetition of an alternative behavior to **replace** an unwanted habitual behavior
8.5	***Overcorrection***	Ask to repeat the wanted behavior in an exaggerated way following an unwanted behavior
8.6	***Generalization of a target behavior***	Advise to perform the wanted behavior, which is already performed in a particular situation, in another situation
8.7	***Graded tasks***	Set easy-to-perform tasks, making them increasingly difficult, but achievable, until behavior is performed

No.	Label	Definition
9. Comparison of outcomes		
9.1	***Credible source***	Present verbal or visual communication from a credible source **in favor of or against the behavior**
9.2	***Pros and cons***	Advise the person to identify and compare reasons for wanting (pros) and not wanting to (cons) change the behavior (includes '**Decisional balance'***)*
9.3	***Comparative imagining of future outcomes***	Prompt or advise the imagining and comparing of future outcomes of changed versus unchanged behavior
10. Reward and threat		
10.1	***Material incentive (behavior)***	Inform that money, vouchers or other valued objects ***will be*** delivered if and only if there has been effort and/or progress in performing the behavior (includes ***'*****Positive reinforcement'**)
10.2	***Material reward (behavior)***	Arrange for the delivery of money, vouchers or other valued objects if and only if there ***has been*** effort and/or progress in performing the behavior (includes '**Positive reinforcement'**)
10.3	***Non-specific reward***	Arrange delivery of a reward if and only if there ***has been*** effort and/or progress in performing the behavior (includes '**Positive reinforcement'**)
10.4	***Social reward***	Arrange verbal or non-verbal reward if and only if there ***has been*** effort and/or progress in performing the behavior (includes '**Positive reinforcement**')
10.5	***Social incentive***	Inform that a verbal or non-verbal reward ***will be*** delivered if and only if there has been effort and/or progress in performing the behavior (includes '**Positive reinforcement'**)
10.6	***Non-specific incentive***	Inform that a reward ***will be*** delivered if and only if there has been effort and/or progress in performing the behavior (includes '**Positive reinforcement'**)
10.7	***Self-incentive***	Plan to reward self in future if and only if there has been effort and/or progress in performing the behavior
10.8	***Incentive (outcome)***	Inform that a reward ***will be*** delivered if and only if there has been effort and/or progress in achieving the behavioral **outcome** (*includes* ***'*****Positive reinforcement'**)
10.9	***Self-reward***	Prompt self-praise or self-reward if and only if there ***has been*** effort and/or progress in performing the behavior
10.10	***Reward (outcome)***	Arrange for the delivery of a reward if and only if there ***has been*** effort and/or progress in achieving the behavioral **outcome** (includes '**Positive reinforcement**')

No.	Label	Definition
10.11	***Future punishment***	Inform that future punishment or removal of reward will be a consequence of performance of an unwanted behavior (may include fear arousal) (includes **'Threat'**)
11. Regulation		
11.1	***Pharmacological support***	Provide, or encourage the use of or adherence to, drugs to facilitate behavior change
11.2	***Reduce negative emotions*** [b]	Advise on ways of reducing negative emotions to facilitate performance of the behavior (includes '**Stress Management**')
11.3	***Conserving mental resources***	Advise on ways of minimizing demands on mental resources to facilitate behavior change
11.4	***Paradoxical instructions***	Advise to engage in some form of the unwanted behavior with the aim of reducing motivation to engage in that behavior
12. Antecedents		
12.1	***Restructuring the physical environment***	Change, or advise to change the **physical** environment in order to facilitate performance of the wanted behavior or create barriers to the unwanted behavior (other than prompts/cues, rewards and punishments)
12.2	***Restructuring the social environment***	Change, or advise to change the **social** environment in order to facilitate performance of the wanted behavior or create barriers to the unwanted behavior (other than prompts/cues, rewards and punishments)
12.3	***Avoidance/reducing exposure to cues for the behavior***	Advise on how to avoid exposure to specific social and contextual/physical cues for the behavior, including changing daily or weekly routines
12.4	***Distraction***	Advise or arrange to use an alternative focus for attention to avoid triggers for unwanted behavior
12.5	***Adding objects to the environment***	Add objects to the environment in order to facilitate performance of the behavior
12.6	***Body changes***	Alter body structure, functioning or support **directly** to facilitate behavior change
13. Identity		
13.1	***Identification of self as role model***	Inform that one's own behavior may be an example to others

No.	Label	Definition
13.2	***Framing/reframing***	Suggest the deliberate adoption of a perspective or new perspective on behavior (e.g. its purpose) in order to change cognitions or emotions about performing the behavior (includes '**Cognitive structuring**'); *If information about consequences, then code **5.1, Information about health consequences, 5.6, Information about emotional consequences** or **5.3, Information about social and environmental consequences** instead of **13.2, Framing/reframing***
13.3	***Incompatible beliefs***	Draw attention to discrepancies between current or past behavior and self-image, in order to create discomfort (includes ***'*Cognitive dissonance'**)
13.4	***Valued self-identity***	Advise the person to write or complete rating scales about a cherished value or personal strength as a means of affirming the person's identity as part of a behavior change strategy (includes ***'*Self-affirmation'**)
13.5	***Identity associated with changed behavior***	Advise the person to construct a new self-identity as someone who 'used to engage with the unwanted behavior'
14. Scheduled consequences		
14.1	***Behavior cost***	Arrange for withdrawal of something valued if and only if an unwanted behavior is performed (includes '**Response cost'**). Note if withdrawal of contingent reward code*, **14.3, Remove reward***
14.2	***Punishment***	Arrange for aversive consequence contingent on the performance of the unwanted behavior
14.3	***Remove reward***	Arrange for discontinuation of contingent reward following performance of the unwanted behavior (includes **'Extinction'**)
14.4	***Reward approximation***	Arrange for reward following any approximation to the target behavior, gradually rewarding only performance closer to the wanted behavior (includes ***'*Shaping'**)
14.5	***Rewarding completion***	Build up behavior by arranging reward following final component of the behavior; gradually add the components of the behavior that occur earlier in the behavioral sequence (includes ***'*Backward chaining'**)
14.6	***Situation-specific reward***	Arrange for reward following the behavior in one situation but not in another (includes ***'*Discrimination training'**)
14.7	***Reward incompatible behavior***	Arrange reward for responding in a manner that is incompatible with a previous response to that situation (includes ***'*Counter-conditioning'**)

No.	Label	Definition
14.8	***Reward alternative behavior***	Arrange reward for performance of an alternative to the unwanted behavior (includes ***'*****Differential reinforcement*****'***)
14.9	***Reduce reward frequency***	Arrange for rewards to be made contingent on increasing duration or frequency of the behavior (includes ***'*****Thinning*****'***)
14.10	***Remove punishment***	Arrange for removal of an unpleasant consequence contingent on performance of the wanted behavior (includes ***'*****Negative reinforcement*****'***)
15. Self-belief		
15.1	***Verbal persuasion about capability***	Tell the person that they can successfully perform the wanted behavior, arguing against self-doubts and asserting that they can and will succeed
15.2	***Mental rehearsal of successful performance***	Advise to practice imagining performing the behavior successfully in relevant contexts
15.3	***Focus on past success***	Advise to think about or list previous successes in performing the behavior (or parts of it)
15.4	***Self-talk***	Prompt positive self-talk (aloud or silently) before and during the behavior
16. Covert learning		
16.1	***Imaginary punishment***	Advise to imagine performing the **unwanted** behavior in a real-life situation followed by imagining an unpleasant consequence (includes ***'*****Covert sensitization*****'***)
16.2	***Imaginary reward***	Advise to imagine performing the **wanted** behavior in a real-life situation followed by imagining a pleasant consequence (includes ***'*****Covert conditioning*****'***)
16.3	***Vicarious consequences***	Prompt observation of the consequences (including rewards and punishments) for others when they perform the behavior

Appendix G

Details of the Behavior Change Wheel intervention functions

Table G1. Behavior Change Wheel intervention functions and definitions (Michie et al., 2014).

No.	Intervention function	Definition
1	Education	Increasing knowledge or understanding.
2	Persuasion	Using communication to induce positive or negative feelings or stimulate action.
3	Incentivization	Creating an expectation of reward.
4	Coercion	Creating an expectation of punishment or cost.
5	Training	Imparting skills.
6	Restriction	Using rules to reduce the opportunity to engage in the target behavior (or to increase the target behavior by reducing the opportunity to engage in competing behaviors).
7	Environmental restructuring	Changing the physical or social context.
8	Modelling	Providing an example for people to aspire to or imitate.
9	Enablement	Increasing means / reducing barriers to increase capability (beyond education and training) or opportunity (beyond environmental restructuring).

Appendix H

Details of articles included in the pilot scoping review

Table H1. Details of six articles included in the pilot scoping review.

Article	Country(s) of study	Population	Animal disease(s)	Zoonotic disease(s)	Behavioral barriers	Behavioral enablers	Behavioral interventions
(Bronner et al., 2015)	France	Cattle producers	Bovine brucellosis	Yes	Yes	Yes	No
(Elbers et al., 2010)	Netherlands	Poultry farmers	Avian influenza	Yes	Yes	Yes	No
(Hamilton-Webb et al., 2016)	England	Animal keepers	Exotic livestock diseases	Not specified	No	Yes	No
(Hopp et al., 2007)	Norway	Sheep farmers	Scrapie	No	Yes	Yes	No
(Tukana et al., 2018)	Fiji, PNG, Vanuatu, and the Solomon Islands	Veterinarians	Not specified	Not specified	Yes	No	No
(Vergne et al., 2016)	Bulgaria, Germany, and the Western Part of the Russian Federation	Pig farmers and wild boar hunters	African swine fever	No	Yes	Yes	No